DANISH MINISTRY
OF THE ENVIRONMENT

Environmental
Protection Agency

Life Cycle Assessment of Biogas from Separated slurry

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Environmental Project No. 1329 2010
Miljøprojekt

Content

Preface

This study, entitled "Life Cycle Assessment of Biogas from Separated slurry" was commissioned by the Environmental Protection Agency of Denmark. It consists of the continuation of the project entitled "Life Cycle Assessment of Management Technologies", available on Environmental Protection Agency of Denmark website (project no. 1298, 2009) and references to it are made several times throughout the present study.

The outcome of this project consists of the present background report and 4 life cycle inventory annexes detailing all the calculations, assumptions and data used for the life cycle assessment of the different biogas production scenarios.

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The project was carried out in the period of August 2009 - December 2009.

This study could not have been performed without the significant contributions from:

- Frank Rosager, Xergi A/S
- Anders Peter Jensen, Xergi A/S
- Henrik Vestergaard Laursen, Xergi A/S
- Jesper Andersen, Xergi A/S

Furthermore, the authors would like to acknowledge the contributions from:

- Karsten Buchhave, Bigadan
- Birgir Norddahl, University of Southern Denmark
- Teodorita Al Seadi, University of Southern Denmark
- Martin Nørregaard Hansen, Agrotech, Institut for Jordbrugs- og Fødevareinnovation
- Henrik B. Møller, Institut for Jorgbrugsteknik
- Lars Jørgen Pedersen, Green Farm Energy A/S

Definitions and abbreviations

Ash. Ash is the remains after heating the dry matter (DM, see below) at 550°C for one hour. Typically, 20% of the dry matter is ash. Another term frequently used for ashes is “fixed solids” (FS).

DM - Dry matter. DM is the fraction of the manure that is left after water has been evaporated due to heating at 80°C to constant weight for typically 24 hours. It typically constitutes 1 – 10% of the slurry by mass (Sommer et al., 2008). ***In Danish: Tørstof (TS).*** It also consists of the total of volatile and fixed solids, and is frequently referred to as “total solids” (TS).

Ecoinvent. Ecoinvent database (v2.0) is a life cycle inventory database containing more than 4000 datasets in a wide variety of areas such as agriculture, energy supply, transport, bioenergy and biomaterials, chemicals, construction materials, packaging materials, metal processing, electronics, etc. These data are internationally recognised as high-quality data and are thoroughly documented with extensive background reports, including uncertainty assessment, and they have been independently reviewed.

LCA - Life Cycle Assessment. LCA is the assessment of the environmental impact of a product (or service) throughout its lifespan, i.e. “from cradle to grave”. The environmental impacts are followed through the whole product chain, typically from raw material extraction, through production and use, to final disposal or recycling. This methodology is standardised by the ISO standards ISO 14044 (ISO, 2006a) and ISO 14040 (ISO, 2006b).

Marginal data (marginal supply). Marginal data are used in consequential LCA. This represents the data from the marginal supply, i.e. the one responding to a minute change in demand on the market in question.

TAN - Total Available Nitrogen: TAN is the sum of NH_3-N + NH_4^+-N. At pH 7.8 almost all the TAN is NH_4^+(only around 1% is NH_3). TAN is often used as synonym for NH_4^+ (assuming that the amount of NH_3 is insignificant), e.g. by Hansen et al. (2008) and by the Danish Norm Data (Poulsen et al. (2001), DJF (2008) and DJF (2008)), which use “NH_4^+” and “TAN” for the same numbers. Strictly speaking, it does not totally cover the same – however, for practice use, they are used as synonyms – also in this study.

VS - Volatile solids. VS are the fraction of DM that volatilises when heating the DM at 550°C for one hour. This is the fraction lost during incineration (Sommer et al., 2008). The content of volatile solids is equal to the difference between the dry matter and ashes (VS = DM – ash). Typically, about 80% of DM is VS for slurry. ***In Danish: Askefrit tørstof eller glødetab.***

VS – easily and heavily degradable. A distinction is made between two types of VS, the easily degradable VS (VS_{ED}) and the heavily (or slowly) degradable VS (VS_{SD}). As opposed to the easily degradable VS, the heavily (or slowly) degradable VS are recalcitrant to microbial degradation (and subsequent transformation to CH_4 and CO_2). Among the different components constituting the VS (e.g. lipid, protein, volatile fatty acids, carbohydrates), this distinction between easily and heavily VS concerns only the carbohydrates (the VS from lipid, protein and volatile fatty acids are considered to be easily degradable only). Sommer et al. (2009) define the heavily degradable VS (VS_{SD}) as the amount of VS in the crude fibre, i.e.: $VD_{SD}=VS_{crude\ fibre}$. The easily degradable VS (VS_{ED}) is defined as the remaining, from the whole VS content: $VS_{ED}= VS – VS_{SD}$.

Slurry: A mixture of all the faeces, urine and some bedding materials (straw, etc.) which is traditionally collected from the pit below the slatted floors. The dry matter content of slurry is typically 1-10% which is lower than for other types of manure, due to addition of washing water and little use of bedding materials.

Slurry "ex animal": Slurry directly after its excretion from the animals (ex-excretion) and before undergoing any further transformation (i.e. losses or addition).

Slurry "ex housing": Slurry leaving the slurry pits in the housing system.

Slurry "ex storage": Slurry after a long time of outdoor storage.

Sammenfatning og konklusioner

De miljømæssige aspekter af biogasproduktion baseret på forbehandlet gylle fra slagtesvin og malkekvæg er undersøgt. Forbehandlingen består i opkoncentrering af gyllen ved hjælp af separationsteknologi. De miljømæssige aspekter er undersøgt ved anvendelse af livscyklusvurdering (LCA) som den grundlæggende metode. Der kan opnås betydelige miljømæssige fordele for både gylle fra slagtesvin og gylle fra malkekvæg sammenlignet med den "konventionelle håndtering af gylle", særligt med hensyn til at reducere bidragene til global opvarmning, men resultaterne afhænger i høj grad af effektiviteten af separationsteknologien før biogasanlægget. Separation efter biogasanlægget kan tilføjes, og dette kan bidrage til en mere effektiv udnyttelse af fosfor, hvilket er inkluderet i undersøgelsen.

Baggrund og formål

Formålet med undersøgelsen "Livscyklusvurdering af biogas baseret på separeret gylle" er at fremme det igangværende arbejde med at etablere et fundament, der muliggør gennemførelsen af livscyklusvurderinger (LCA) af gyllebehandlingsteknologier i Danmark. Dette er nu blevet udbygget med biogasscenarier.

Resultaterne af undersøgelsen er:

- En database, der indeholder livscyklusdata for 4 biogasscenarier.
- En rapport, der indeholder resultaterne af livscyklusvurderingerne for de fire biogasscenarier.
- Fire detaljerede annekser, der beskriver de anvendte data, beregninger og massebalancer (i rapporten).

Formålet med undersøgelsen har været at give et svar på spørgsmålet:
"Hvad er de miljømæssige fordele og ulemper ved at bruge gylle fra slagtesvin eller malkekvæg til biogasproduktion, i stedet for at bruge den rå gylle som gødning ved at udbringe den til marker uden forudgående behandling?"

I undersøgelsen vurderes fire forskellige biogasscenarier med gylle som eneste input til processen (dvs. uden supplerende tilsætning af let nedbrydelige kulstofforbindelser). Selv om biogas fremstillet udelukkende med gylle som input endnu ikke er den mest udbredte praksis i Danmark, er det sandsynligt, at dette bliver et vigtigt alternativ i Danmark fremover, både på grund af regeringens mål om at halvdelen af al husdyrgødning i 2020 skal bruges til grøn energi (jf. "Grøn Vækst"), men også fordi der er begrænset adgang til andre kulstofkilder (f.eks. organisk affald) som omsættes sammen med gyllen.

Undersøgelsen er en fortsættelse af projektet "Livscyklusvurdering af gylle-håndteringsteknologier", som blev startet af "Partnerskab for Industriel Bioteknologi". Begge projekter er udført for Miljøstyrelsen.

Undersøgelsen

Undersøgelsen inkluderer fire biogasscenarier:

- Scenarie F: Biogasproduktion baseret på en blanding af rå svinegylle og fiberfraktionen fra kemisk-mekanisk separation (dekanter centrifuge kombineret med tilsætning af kationisk polyacrylamid polymer for at øge effektiviteten af separationen). Biogassen anvendes til produktion af el og varme. Efter biogasanlægget bliver den afgassede biomasse separeret for at kunne fordele gyllens indhold af fosfor mere hensigtsmæssigt (dvs. til områder med fosfor-mangel).

- Scenarie G: Som ovenfor, men med gylle fra malkekvæg.

- Scenarie H: Biogasproduktion baseret på en blanding af rå svinegylle og fiberfraktionen fra mekanisk separation (skruepresse). Biogassen anvendes til produktion af el og varme. Der er ingen separation efter biogasanlægget.

- Scenarie I: Som ovenfor, men biogasproduktion er baseret på rå gylle og fiber piller (baseret på svinegylle).

Hovedkonklusioner

Baseret på resultaterne af undersøgelsen kan det konkluderes at:

- De miljømæssige fordele ved biogas fra separeret gylle er meget afhængige af effektiviteten af separationen (for kulstof, kvælstof og fosfor). Dette gælder især for kulstof, da effektiviteten af separationen afgør, i hvilket omfang de let-nedbrydelige kulstof forbindelser i gyllen bliver overført til biogasanlægget. Effektiv separation kan opnås ved tilsætning af polymer, men også ved brug af en velegnet separations-teknologi. Det kan nævnes, at den anvendte dekanter centrifugerings-teknologi har en forholdsvis høj effektivitet med hensyn til at overføre kulstofforbindelser til fiberfraktionen også uden brug af polymer.

- Produktion af biogas baseret på separeret gylle kan føre til betydelige reduktioner af gylles bidrag til den globale opvarmning, forudsat at den ”bedst tilgængelige teknologi”, der er beskrevet i rapporten, er anvendt. Det omfatter bl.a.:
    - at fiberfraktionen opbevares overdækket, og at der kun er kort tids lagring af fiberfraktionen, før den transporteres til biogasanlægget,
    - at biogasproduktionen foregår i 2 trin, og at den sekundære reaktor er overdækket med et lufttæt lag (således at emissionerne af metan minimeres),
    - at fiberfraktionen fra den separerede afgassede gylle opbevares overdækket.

De miljømæssige fordele er endvidere meget afhængige af hvilken energikilde den producerede kraftvarme fra biogassen substituerer.

- På grundlag af dokumentation baseret på flere forskellige referencer vil den kationiske polyacrylamidpolymer, der tilsættes under separationen før biogasanlægget, sandsynligvis ikke nedbrydes i biogasanlægget, men spredes til jord via de afgassede biomassefraktioner. De fundne referencer tyder også på, at denne polymer er forholdsvis modstandsdygtig overfor nedbrydning, i det mindste under de betingelser, der findes i landbrugsjorden. Det er på den baggrund sandsynligt, at polymeren ophobes i miljøet. Flere undersøgelser er nødvendige for at kunne udtale sig om en eventuel potentiel toksicitet af dette aspekt.

Projektresultater

De miljømæssige fordele er opgjort per ton gylle ab dyr for at sikre et fælles grundlag for sammenligningerne mellem teknologierne.

Miljøvurderingerne af biogasproduktion baseret på en blanding af rå og separeret gylle er blevet udført ved at sammenligne de udvalgte biogasscenarier med et referencescenarie. Referencescenarie er fastlagt som den ”konventionelle” måde at håndtere gylle på, dvs. at gyllen lagres indtil den kan spredes på marken, hvorved gyllens gødningsværdi udnyttes. Livscyklusmetodikken danner grundlag for sammenligningen.

For de biogasscenarier, der inkluderer en effektiv separationsteknologi inden biogasanlægget, er der fundet en række interessante resultater:

- De samlede bidrag til global opvarmning reduceres betydeligt, når gyllen anvendes til biogasproduktion frem for på den konventionelle måde. Reduktionen skyldes især to faktorer:
  - Reduktion of emissionerne af metan fra lagring af gyllefraktionerne. Reduktionerne skyldes:
    - Separationen før biogasanlægget medfører en overførsel af letnedbrydelige kulstofforbindelser til fiberfraktionen, hvilket bevirker at metanemissionerne fra den flydende fraktion reduceres betydeligt under den efterfølgende lagring.
    - Omdannelsen af let nedbrydelige kulstofforbindelser i biogasanlægget resulterer i et lavere potentiale for metanemissioner i den efterfølgende lagring af den afgassede biomasse (og fraktionerne heraf).
  - Den producerede biogas anvendes til produktion af el og varme, og dette erstatter el og varme baseret på fossile brændstoffer, som derfor trækkes fra systemet.

- Bidraget til miljøeffekten ”forsuring” er ikke væsentligt lavere for biogasscenarierne end for referencescenariet.

- For miljøeffekten ”eutrofiering med kvælstof” (også kendt som udvaskning af kvælstof til vandmiljøet) er der ikke signifikante forskelle mellem biogasscenarierne og referencescenariet.

- For miljøeffekten ”fotokemisk ozondannelse” (eller ”smog”) er der ikke er nogen signifikant forskel mellem biogasscenariet og den konventionelle gyllehåndtering i referencescenariet. I biogasscenarierne er emissionerne af metan fra lagring af gyllefraktionerne markant lavere end fra lagring af gyllen i referencescenariet, men dette opvejes af bidragene fra emissioner af NO_x fra forbrænding af biogas under kraftvarmeproduktionen.

- I de to biogasscenarier, der indbefatter separering efter biogasanlægget, er der et reduceret forbrug af fosforressourcer. Dette reducerer endvidere fosfor-eutrofiering af vandmiljøet, da udvinding af fosfor-ressourcer og produktion af fosfor-gødning bidrager til dette. Disse fordele afhænger dog af følgende forudsætning:
    - Den indvundne fosfor fra separationen skal anvendes i områder med fosfor-mangel (dvs. ikke anvendes i områder med fosfor-overskud).

- For miljøeffekten "uorganiske stoffer der påvirker åndedrættet" (emissioner af små partikler, ofte kendt fra dieselbiler) opnås ingen væsentlige miljømæssige fordele. Dette er hovedsageligt på grund af emission af nitrogenoxider, der genereres ved forbrændingen af biogas i biogasmotoren ved kraftvarmeproduktionen, men også på grund af de højere emissioner af NH_3, der opstår under lagring af den afgassede fiberfraktionen.

- Forbrug af "ikke-vedvarende energi" skyldes især transport og forbrug af elektricitet. Biogasscenarierne indebærer lidt mere transport, men dette opvejes af de fossile brændstoffer, der erstattes af den producerede kraft varme. Samlet set giver biogasscenarierne en betydelig reduktion af forbruget af ikke-vedvarende energi.

- Undersøgelsen har inkluderet opgørelser og massestrømsbalancer for biogent kulstof. Ud fra resultaterne kan der drages følgende konklusioner:
    - Emissionerne af biogent CO_2 fra gylle udgør omkring 50 % af de positive bidrag til global opvarmning for biogasscenarierne. Andelen er en anelse lavere for referencescenariet.
    - I biogasscenarierne er emissionerne af biogent CO_2 fra marken reduceret i forhold til i referencescenariet, men dette skyldes hovedsageligt, at de let omsættelige kulstofforbindelser omsættes i biogasanlægget, således at omsætningen blot sker i biogasanlægget i stedet for på marken – og det biogene CO_2 blot udledes når biogassen forbrændes ved kraftvarmeproduktionen i stedet for på marken.
    - Mængden af kulstof, der bindes i jorden og som derfor ikke udledes i atmosfæren som CO_2, kan bestemmes som forskellen mellem den mængde kulstof, der tilføres jorden via gyllen og mængden af biogene CO_2-emissioner fra marken. Der bindes mindre kulstof i jorden i biogasscenarierne, da der er mindre kulstof til rådighed i afgasset gylle i forhold til rå gylle. Dog skal det understreges, at forskellene er temmelig små.

For det biogasscenarie, der er baseret på separeringsteknologi med lav effektivitet, og for det biogasscenarie, der er baseret på tilførsel af fiberpiller, er der ikke fundet væsentlige miljømæssige fordele. Kun for global opvarmning og for forbrug af ikke-vedvarende energi er der reduktioner, men disse er imidlertid meget mindre i forhold til de biogasscenarier, der er baseret på separationsteknologi med høj separationseffektivitet. Det skyldes meget simpelt, at hvis separationseffektiviteten er lav, overføres de let-omsættelige kulstofforbindelser ikke til fiberfraktionen (som transporteres videre til biogasanlægget) men bliver i den tynde fraktion, der bliver lagret og spredt på marken hos landmanden parallelt med den ubehandlede gylle i referencescenariet.

For alle biogasscenarier – både dem med høj separationseffektivitet og for dem med lav separationseffektivitet – gælder det, at de resulterer i gylle med højere kvælstoftilgængelighed og der opstår dermed et potentiale for udbyttestigning. Denne udbyttestigning er inkluderet og omsat til produktion af dansk hvede, (hvorved det ekstra udbytte erstatter hvede, der ellers skulle have været produceret, hvorfor dette trækkes fra systemerne). Det skal dog bemærkes, at det ekstra udbytte er forholdsvis lille, og at de miljømæssige konsekvenser af dette ikke bidrager væsentligt til at reducere den samlede netto-virkningen af de forskellige miljøpåvirkninger. En yderligere undersøgelse af hvilke afgrøder, der undgås, er ikke inkluderet.

For alle scenarier er der to store ”hot spots”, der bidrager til flere af miljøeffekterne: Opbevaring af gylle i stalden (hovedsageligt pga. emissioner af NH_3 og CH_4) og processerne efter gyllen er spredt på marken. Disse repræsenterer muligheder for forbedringer af de samlede miljøbelastninger fra gylle, og dermed også for biogasscenarierne.

Opbevaring af fiberfraktionen før og efter biogasanlægget er afgørende for det samlede bidrag til især global opvarmning og forsuring. Afdækning af fiberfraktionen under lagring kan reducere den globale opvarmning.

Disse resultater gælder for danske forhold, og kan ikke umiddelbart overføres til lande med andet klima, anden lovgivning vedr. næringsstofregulering eller andre produktionssystemer.

Summary and conclusions

The environmental aspects of biogas production based on pre-treated slurry from fattening pigs and dairy cows have been investigated in a life cycle perspective. The pre-treatment consists of concentrating the slurry using a separation technology. Significant environmental benefits, compared to the status quo slurry management, can be obtained for both pig and cow slurry, especially regarding reductions of the contributions to global warming, but the results depend to a large extent on the efficiency of the separation technology. Adding separation after the biogas plant can contribute to a more efficient management of the phosphorus, and this has also been investigated.

Background and objectives

The objective of the study “Life Cycle Assessment of Biogas from Separated slurry” has been to foster the on-going work on a foundation for Life Cycle Assessment of slurry management in Denmark by biogas production scenarios.

The outcomes of the study are:

- A database containing Life Cycle Inventory data for 4 selected biogas scenarios;
- A report, containing the Life Cycle Assessment results and the interpretation of these for the four biogas scenarios;
- Four detailed Annexes describing all data used, calculations and mass balances.

The goal of the study has been to provide an answer to the question:
“What are the environmental benefits and disadvantages of using fattening pig slurry or dairy cow slurry for biogas production instead of using the raw slurry as an organic fertiliser and spread it on land without any prior treatment?”

This project assesses four biogas production alternatives where slurry is the only input in the process (i.e. without supplementary addition of easily degradable carbon). Although biogas produced exclusively from slurry input is not yet the most common practice in Denmark, it is likely to become an important alternative for the Danish panorama. This is due to the target to use more slurry for biogas production, but also to the limited availability of the carbon-source materials that are actually co-digested with the slurry.

The study is a continuation of the project “Life Cycle Assessment of Slurry Management Technologies”, initiated by “Partnership for Industrial Biotechnology”. Both projects are commissioned by the Environmental Protection Agency of Denmark.

Scope

The study includes 4 biogas scenarios:

- Scenario F: Biogas production based on a mixture of raw pig slurry and fibre fraction from chemical-mechanical separation technology (decanter centrifuge combined with the addition of cationic polyacrylamide polymer for increasing the separation efficiency). The biogas is used for co-generation of heat and electricity. After the biogas plant, the degassed biomass is separated by a decanter centrifuge in order to facilitate an optimised utilisation of the phosphorous content of the degassed biomass (i.e. to fields with phosphorous deficiency).

- Scenario G: As above, but with dairy cow slurry.

- Scenario H: Biogas production based on a mixture of raw pig slurry and fibre fraction from mechanical separation technology (screw press). The biogas is used for co-generation of heat and electricity. No separation is performed after the biogas plant.

- Scenario I: As above, but the biogas production is based on raw slurry and processed fibre pellets.

Main conclusions

Based on the results of the study it can be concluded that:

- The environmental benefits of biogas from separated slurry are very dependent upon the separation efficiency (for carbon, nitrogen and phosphorous). This particularly applies for carbon, as the separation efficiency defines the extent to which the degradable carbon contained in the slurry is transferred to the biogas plant. Efficient separation can be obtained by using polymer, but also by using a suitable separation technology. It could be mentioned that the decanter centrifuge used has a rather high efficiency of transferring volatile solids (VS) to the fibre fraction also without the use of polymer.

- Biogas production from separated slurry can lead to significant reductions in the contributions to global warming, provided that the “best available technologies” described in the report are used. That includes, among others:
  - a covered and short time storage of the fibre fraction before entering the biogas plant,
  - a 2-step biogas production where the post-digestion tank is covered with air-tight cover,
  - a covered storage of the degassed fibre fraction

The benefits are also highly dependent upon the source of energy substituted by the biogas.

- Based on evidences from reviewed studies, the cationic polyacrylamide polymer added during separation is probably not degraded in the biogas plant, but spread to land through the degassed biomass fractions. These evidences also suggest that this polymer is rather recalcitrant to degradation, at least under the conditions found in an agricultural field. Therefore, it is suggested that the polymer is likely to accumulate and persist in the environment. More investigation is needed before a final prove or disproval of the potential toxicity of this aspect.

Project results

The overall environmental benefits are expressed per ton of slurry ex animal in order to ensure a common ground for comparisons between technologies. This is the basis on which the results of this study rely.

The environmental assessment of biogas production scenarios based on a mixture of raw and separated slurry has been performed by comparing the selected biogas scenarios with a reference scenario. This reference scenario is defined as the "conventional" way of managing slurry, i.e. storing it and applying it to the field as an organic fertiliser. The Life Cycle Assessment methodology forms the basis for the comparison.

For the biogas scenarios involving an efficient separation technology before the biogas production, the following results have been found:

- The overall contribution to the impact "global warming" is significantly reduced when using the slurry for biogas production compared to using the slurry the conventional way. The reduction is mainly caused by two factors:
  - Reduction of methane emissions from storage of the slurry fractions. The reductions are caused by:
    - The separation before the biogas plant provides a transfer the easily degradable carbon to the fibre fraction which leaves the liquid fraction with a reduced potential for methane emissions during storage.
    - The conversion of the easily degradable carbon to biogas in the biogas plant, resulting in a lower potential for methane emissions in subsequent storage.
  - The produced biogas is used for production of electricity and heat, and this replaces electricity and heat based on fossil fuels which is accordingly subtracted from the system.

- The contribution to the environmental impact "acidification" is not significantly lower for the biogas scenarios compared to the reference scenario.

- For the impact category "eutrophication with nitrogen" (also known as nitrogen leaching to aquatic recipients) the small reductions obtained with the biogas scenarios can hardly be claimed as significant when taking the uncertainties into consideration.

- For the impact "photochemical ozone formation" (or "smog") there is no significant difference between the biogas scenario as compared to the conventional slurry management. This is mainly caused by a significantly lower methane emission from the storage of the slurry fractions, which is, however, counterbalanced by contributions from the emissions of NO_x from the combustion of biogas during the co-production of and heat and power.

- The consumption of phosphorus resources are reduced in the two biogas scenarios, including a separation after the biogas plant (Scenarios F and G). Furthermore, this reduces the eutrophication of aquatic recipients by phosphorus when extracting these resources. However, these benefits depend upon the following pre-condition:
  - The recovered phosphorous must be used in fields with phosphorous deficiency (i.e. not applied in excess).

- No significant environmental benefits are obtained for the category “respiratory inorganics”, which reflects the emissions of particulate matters. This is mostly because of the emission of nitrous oxides generated during the combustion of the biogas in the biogas engine, but also because of the higher NH_3 emissions involved during the storage of the degassed fibre fraction.

- For the impact “non-renewable energy”, transport and consumption of electricity is significant. The biogas scenarios involves slightly more transport, however, this is by far counterbalanced by the fossil fuels that is replaces by the produced electricity and heat. Overall, the biogas scenarios allow significant reductions of non-renewable energy.

- The flow of biogenic carbon was included in this study. As a result, the following conclusions can be drawn:
  - The emissions of biogenic CO_2 from the slurry represent about 50 % of the positive contributions to global warming for the biogas scenarios. This is slightly lower for the reference scenario.
  - For the impact “global warming”, reductions of biogenic CO_2 emissions from field are obtained with the biogas scenarios. However, this is mainly due to the fact that the easily degradable carbon is converted in the biogas plant, and hence, the conversion occurs there instead of in the field.
  - The amount of carbon sequestrated in the soil (and accordingly not emitted in the atmosphere) could be determined as the difference between the carbon applied with the slurry and the biogenic CO_2 emitted. The sequestrated carbon is lower with the biogas scenarios, since there is less carbon available for sequestration in degassed slurry as compared to raw slurry. However, these represent rather small differences.

No significant environmental benefits were obtained for the biogas scenario involving a separation technology with a low efficiency and the use of processed fibre pellets for the biogas production. For the biogas scenario involving a separation technology with a low efficiency and the used of fibre fraction for the biogas production, the only significant environmental benefits apply to the impact “global warming” and the impact “non-renewable energy”. The magnitude of these benefits is however much smaller as compared to the scenarios involving a separation technology with high separation efficiency.

For both separation technology types (high and low efficiency), the biogas scenarios resulted in a slurry with higher nitrogen availability and thereby a potential for yield increase. This was taken into account and translated into the production of Danish wheat that is avoided through this increased yield. However, this represented a rather small difference and did not contribute significantly to reduce the overall net impact of the different environmental impact categories considered.

For all scenarios, there are two major hot spots contributing to the impact categories assessed: in-house slurry storage (mostly through NH_3 and CH_4) and field processes. These represent opportunities for potential improvement of the overall environmental performance of the biogas scenarios assessed.

The storage of the fibre fraction before and after the biogas plant is crucial for the overall contributions to especially global warming and acidification. Uncovered storage of the fibre fraction may reduce the global warming benefits of the scenarios assessed.

These results only apply for Danish conditions and the results cannot be transferred to other countries with different climate, different production systems and different laws and rules regarding regulation of nutrients.

1 Introduction and objectives

1.1 Background

The Danish Environmental Protection Agency, in collaboration with different companies and organisations active in Denmark, initiated the preparation of a foundation for Life Cycle Assessment (LCA) for slurry management technologies. As a result, a recent LCA report was released assessing five different scenarios of slurry management (including a reference scenario for both fattening pigs and dairy cows slurry management), highlighting the environmental consequences and hot spots of these slurry management scenarios.

The present study represents a continuation of this foundation and build on the same reference scenarios. However, the emphasis of the present study is on different biogas production scenarios. In fact, anaerobic digestion of animal slurry has many acknowledged benefits such as: the production of a biogas rich in methane that can be used as a renewable energy source, mitigations effect on greenhouse gas and the production of an organic fertiliser having enhanced agronomic properties (as compared to raw slurry). In a high animal density country such as Denmark, anaerobic digestion therefore represents an interesting avenue not only for manure management, but also for renewable energy production, given the large quantities of slurry produced. Moreover, the target to use 40 % of all the slurry produced in Denmark for biogas production by 2020 has been announced many times, as well as the possibility to eventually use all manure produced in Denmark for biogas production. Currently, it is approximately only 5 % of the slurry that is digested for biogas production.

This project assesses four biogas production alternatives where, in all cases, slurry is the only input to the process. Although biogas produced exclusively from slurry input (i.e. without supplementary addition of easily degradable carbon) is not yet the most common practice in Denmark, it is likely to become an important alternative for the Danish panorama. This is due to the target to use more slurry for biogas production, but also to the limited availability of the C-source materials that are actually co-digested with the slurry.

As for the first publication of this LCA foundation initiative for slurry management technologies, the participating companies and organisations have agreed to put their own data, mass balances and emissions data at the disposal.

1.2 Objectives and goal of the study

The objective of the present study is to foster the on-going LCA foundation for Life Cycle Assessment of slurry management in Denmark (described in Wesnæs et al., 2009) by biogas production scenarios.

The outcomes of this study are:

- A database containing Life Cycle data for the four selected biogas scenarios;
- This report, containing the Life Cycle Assessment results and the interpretation of these for the four selected biogas scenarios;
- Four detailed Annexes describing the calculation methodologies used, the data as well as the mass balances for the different process flows.

The goal of this study is the same as in the first part of this on-going LCA foundation for Life Cycle Assessment of slurry management in Denmark, i.e. to provide an answer to the following question:

"What are the environmental benefits and disadvantages of introducing this technology for slurry management?"

Therefore, all biogas scenarios established in this study will be compared to the reference slurry management scenario established in Wesnæs et al. (2009), i.e. using raw slurry as an organic fertiliser and spread it on land without any prior treatment.

The results of this study are intended for public disclosure and will be communicated to all participating companies and organisations. They are intended to provide a rigorous and documented support to decision making as regarding the implementation of the different biogas technologies presented in this study (as an alternative to the conventional slurry management).

1.3 Organisation, Participants and Target Groups

This study was commissioned by the Environmental Protection Agency of Denmark. The project was carried out in the period August 2009 - December 2009 for a budget corresponding to approximately 1½ month of fulltime work.

The steering committee for the study includes:

- Peter H. Schaarup, Environmental Protection Agency of Denmark
- Anton Rasmussen, Environmental Protection Agency of Denmark
- Thomas Alstrup, FORA
- Frank Rosager, Xergi A/S
- Michael Støckler, Agro Business Park
- Jesper Kløverpris, Novozymes
- Thomas Schrøder, Novozymes
- Gunnar Hald Mikkelsen, Samson-Agro A/S
- Thorbjørn Machholm, Grundfos Management A/S
- Jesper Ravn Lorenzen, Grundfos New Business A/S

This study could not have been performed without the significant contributions from:

- Frank Rosager, Xergi A/S
- Anders Peter Jensen, Xergi A/S
- Henrik Vestergaard Laursen, Xergi A/S
- Jesper Andersen, Xergi A/S

Furthermore, the authors would like to acknowledge the contributions from:

- Karsten Buchhave, Bigadan
- Birgir Norddahl, University of Southern Denmark
- Teodorita Al Seadi, University of Southern Denmark
- Martin Nørregaard Hansen, Agrotech, Institut for Jordbrugs- og Fødevareinnovation
- Henrik B. Møller, Institut for Jordbrugsteknik
- Lars Jørgen Pedersen, Green Farm Energy A/S

The study has been carried out by Lorie Hamelin, Marianne Wesnæs and Henrik Wenzel from the University of Southern Denmark in close collaboration with Bjørn Molt Petersen, Department of Agroecology and Environment, Faculty of Agricultural Sciences, Aarhus University.

2 Scope

2.1 Methodology

The methodology used in this study is Life Cycle Assessment, and is standardised by international standards ISO 14044 (ISO, 2006a) and ISO 14040 (ISO, 2006b). This methodology assesses, for the whole life-cycle of a given product or service, the environmental impacts generated as a consequence to this product or service.

According to the ISO standards 14044 and 14040 (ISO, 2006a; ISO, 2006b), a LCA is an iterative methodology including four main phases:

- Goal and scope definition phase: This includes, among others, a clear definition of the study goal, the definition of a functional unit to which all the inputs and outputs flows are related as well as the description of the system boundaries.

- Inventory analysis phase: This involves the compilation and quantification of all inputs and outputs comprised within the boundaries defined.

- Impact assessment phase: In this phase, all substances are related to a specific environmental impact category, thus allowing to highlight the environmental significance of all processes. This comprises (at least) the two following steps:

    - Characterisation: This consists of the quantification of the contribution of each inventoried substances to a specific impact category (ISO, 2006a). To do this, a “reference substance” is defined for each impact categories and the contribution from the other substances to the impact category is calculated relative to this “reference substance” (e.g. global warming is expressed in kg CO_2 equivalents). Different methodologies are available to carry out this characterisation, and this study uses, unless otherwise stated, the Danish EDIP method by Wenzel et al. (1997) as well as the updates of this methodology (Weidema et al., 2004; Weidema, 2004; Stranddorf et al., 2005; Hauschild and Potting, 2005; Potting et al., 2003).

    - Normalization: According to ISO 14044 (ISO, 2006a), the aim of the normalization is to allow a better understanding of the relative magnitude of the different impact categories results, i.e. easing the comparison between impacts affecting the environment in a quite different way. Normalization therefore transforms the results of the impacts categories (expressed according to a given indicator) by dividing them by a selected reference value. In this project, the reference values considered for normalization is the yearly total emission (global / regional / local) per person (worldwide/regionally/locally). The contribution of all processes to the different environmental impact categories is therefore expressed per "person equivalent", so this makes the comparison possible between the different environmental impact categories. The normalization factors used in this project are, unless otherwise stated, based on those listed in the Danish EDIP method by Wenzel et al. (1997) as well as the updates of this methodology (Stranddorf et al., 2005; Hauschild and Potting, 2005; Potting et al., 2003).

- Interpretation phase: This is the phase where the results of the previous phases are summarised and discussed. Recommendations can be drawn from this phase.

The present study is a comparative study; all four biogas scenarios will be compared to the reference scenario established and described by Wesnæs et al. (2009). The primary data for the technologies in this study are delivered by the producers of these technologies. Background data are from the Ecoinvent database (v2.0) as it is acknowledged that this is the most reliable and high-quality database for Life Cycle Inventory data, providing transparent, independent and consistent data for a large variety of processes. The Ecoinvent database structure and supporting material is described in more details by Frischknecht et al. (2007). Access to the Ecoinvent database requires a licence (Ecoinvent Centre, 2009).

The modelling has been carried out by the use of the Simapro 7.1 LCA software. Details about the software can be found in PRé Consultants (2009). The use of this software also requires a license.

2.2 System overview: reference scenarios and alternatives

2.2.1 Reference Scenario (Scenario A)

The reference scenario used in this study reflects the conventional slurry management practices for both fattening pig slurry and dairy cow slurry, i.e. the slurry is used as an organic fertiliser and is spread to land without any prior treatment. For both fattening pig and dairy cow slurry, the reference scenario can be summarised as the following three main stages:

- In-house storage: Once excreted, animal defecations contribute to slurry generation which is then stored in-house in the slurry pit below the animals. On a regular basis, the pits are emptied and the slurry is then temporarily transferred to an outdoor pre-tank.
- Outdoor storage: From the pre-tank, the slurry is transferred to an outdoor covered storage tank, made of concrete. The cover consists of a natural crust cover in the case of dairy cows slurry and of a cut straw cover in the case of fattening pig slurry. Slurry will remain in the storage tank until the suitable period for field fertilisation.
- Transport and field processes: When suitable, the slurry will be pumped from the storage tank, transported to the field and applied to the fields to be fertilised.

The in-housing slurry composition, which is the very basis for the various changes slurry undergoes according to the alternative studied, is described in the reference scenario (Annex A of Wesnæs et al., 2009 for an comprehensive description; Annex A of this study for a summarised description).

The reference scenario used in the present study is the same as extensively described in Wesnæs et al. (2009), unless when otherwise specified. Some of the key processes described in Wesnæs et al. (2009) for the reference scenario are also described in Annex A of the present report.

All the alternative biogas treatments investigated in this study will be compared to this reference scenario.

2.2.2 Biogas from raw pig slurry and fibre fraction from chemical-mechanical separation (Scenario F)

This scenario considers the production of biogas with the two following inputs:

- Raw manure from fattening pig slurry;
- Fibre fraction obtained from a chemical-mechanical separation process of raw pig slurry.

These fractions do not necessarily come from the same farm (and most probably they do not), but they both end up at the biogas plant. Once at the biogas plant, these fractions are mixed according to their composition and to their degradability in order to achieve realistic production conditions.

This scenario shall be seen as a scenario including “best available technologies” for biogas production.

This scenario can be summarised with the 4 following processes:

- In-house storage: As for the reference scenario, the raw slurry is stored in-house and temporarily in the outdoor pre-tank. A part of this slurry will be separated and a part of this slurry will be transported to a biogas plant in order to serve directly as an input for biogas production.
- Slurry separation prior to biogas production: Part of the stored slurry is separated through a decanter centrifuge separation technology, including the addition of cationic polyacrylamide polymer in the slurry for increasing the separation efficiency.
    - Liquid fraction: The liquid fraction is stored in an outdoor storage and when suitable, transported and applied to fields for fertilisation purposes.
    - Fibre fraction: The fibre fraction is transported to a biogas plant in order to serve as an input for biogas production.
- Biogas production: The raw slurry and the fibre fraction are used as inputs in a biogas plant for producing biogas. The biogas is used to run a biogas engine and co-generate heat and electricity.
- Slurry separation post biogas production: The degassed slurry from the biogas plant is separated with a decanter centrifuge, but here, no polymer is added.

    - Liquid fraction: The degassed liquid fraction is stored in an outdoor storage and when suitable, transported and applied to fields for fertilisation purposes.
    - Fibre fraction: The degassed fibre fraction is stored outdoor in a covered heap and when suitable, transported and applied to fields lacking phosphorus for fertilisation purposes.

This biogas scenario is extensively described in Annex F of this report, including all mass balances, assumptions and detailed calculations.

2.2.3 Biogas from raw cow slurry and fibre fraction from chemical-mechanical separation (Scenario G)

This scenario considers the production of biogas with the two following inputs:

- Raw manure from dairy cow slurry;
- Fibre fraction obtained from a chemical-mechanical separation process of raw dairy cow slurry

This scenario shall be seen as a scenario including “best available technologies” for biogas production.

This scenario can be summarised by the exact same processes as described in section 2.2.2 (however, the slurry origins from dairy cows instead of fattening pigs). An extensive description of all mass balances, assumptions and calculations involved in this scenario is presented in Annex G of the present report.

2.2.4 Biogas from raw pig slurry and fibre fraction from mechanical separation (Scenario H)

This scenario considers the production of biogas from the two following inputs:

- Raw manure from fattening pig slurry;
- Fibre fraction obtained from a mechanical separation process of raw pig slurry.

The mechanical separation considered is the screw press separation technology extensively described in Annex C of Wesnæs et al. (2009).
This scenario can be summarised with the 4 following processes:

- In-house storage: As for the previous scenarios, the raw slurry is stored in-house and temporarily in the outdoor pre-tank. A part of this slurry will be separated and a part of this slurry will be transported to a biogas plant in order to serve directly as an input for biogas production.

- Slurry separation: Part of the stored slurry is separated through a mechanical separation technology (screw press). This separation process is the same as assessed in Wesnæs et al. (2009), Annex C.
    - Liquid fraction: The liquid fraction is stored in an outdoor storage and when suitable, transported and applied to fields for fertilisation purposes.
    - Fibre fraction: The fibre fraction is transported to the biogas plant in order to serve as an input for biogas production.

- Biogas production: The raw slurry and the fibre fraction are used as inputs in a biogas plant for producing biogas. The biogas is used to run a biogas engine and co-generate heat and electricity.
- Fate of the degassed slurry: The degassed slurry is stored in an outdoor storage covered by a straw cover and transported to the field when suitable for fertilisation operations. The digested slurry is then applied to the fields to be fertilised.

This biogas scenario is extensively described in Annex H of this report, including all mass balances, assumptions and detailed calculations.

2.2.5 Biogas from raw slurry and processed fibre pellets (Scenario I)

This scenario considers the production of biogas from the two following inputs:

- Raw manure from fattening pig slurry;
- Fibre pellets obtained from drying and pressing the fibre fraction from mechanically separated fattening pig slurry (mechanical separation by the same screw press technology used in Scenario H).

The fibre pellets process is the same as extensively described in Annex D of Wesnæs et al. (2009).

This scenario can be summarised with the 4 following processes:

- In-house storage: As for the previous scenarios, the raw slurry is stored in-house and temporarily in the outdoor pre-tank. A part of this slurry will be separated and a part of this slurry will be transported to a biogas plant in order to serve directly as an input for biogas production.
- Slurry separation: Part of the stored slurry is separated through a mechanical separation technology (screw press). This separation process is the same as assessed in Wesnæs et al. (2009), Annex C.
    - Liquid fraction: The liquid fraction is stored in an outdoor storage and when suitable, transported and applied to fields for fertilisation purposes.
    - Fibre fraction: The fibre fraction undergoes further processing in order to produce fibre pellets. The process for production of fibre pellets is the same as assessed in Wesnæs et al. (2009), Annex D. The fibre pellets are transported to the biogas plant in order to serve as an input for biogas production.
- Biogas production: The raw slurry and the fibre pellets are used as inputs in a biogas plant for producing biogas. The biogas is used to run a biogas engine and co-generate heat and electricity.
- Fate of the degassed slurry: The degassed slurry is stored in an outdoor storage covered by a straw cover and transported to the field when suitable for fertilisation operations. The digested slurry is then applied to the fields to be fertilised.

This biogas scenario is extensively described in Annex I of this report, including all mass balances, assumptions and detailed calculations.

2.2.6 Overview of the 4 alternative biogas scenarios and of the reference scenario

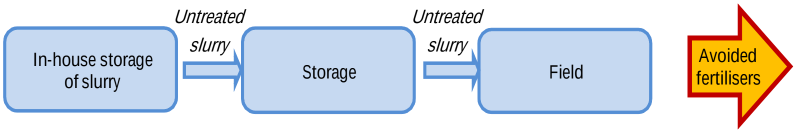
Some similarities can be noted between the biogas scenarios described in section 2.2.2 to 2.2.5. Scenario F and G are in fact mostly identical, the only difference being that scenario F assesses fattening pig slurry and scenario G assesses dairy cow slurry. The particularity of these two scenarios is that they use a chemical-mechanical separation process prior to the biogas production, which is anticipated to produce a fibre fraction rich in VS and thereby suitable for biogas production. These scenarios also involved a second separation after the biogas production, which is expected to produce a fibre fraction rich in phosphorus.

Scenario H differs from scenario F as this second separation is not performed and as the first separation does not involve the use of polymer. Scenario I, as opposed to scenarios H and F, does not use fibre fraction as an input for biogas production but fibre pellets (produced as a result of further processing of the mechanical fraction).

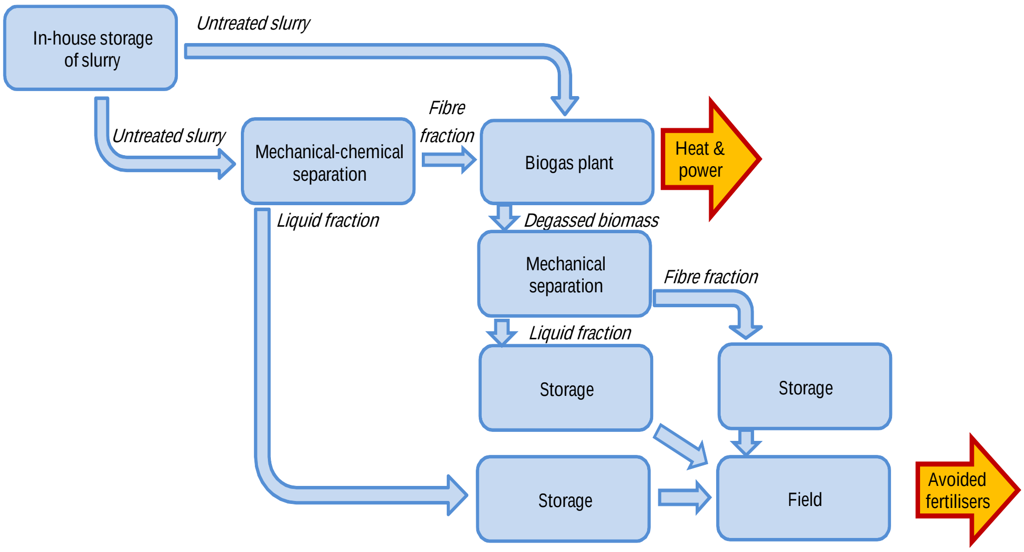
Figure 2.1 schematised the 4 alternative biogas scenarios and the reference scenario.

Figure 2.1.
Simplified illustration of the reference scenario and the 4 alternative biogas scenarios considered

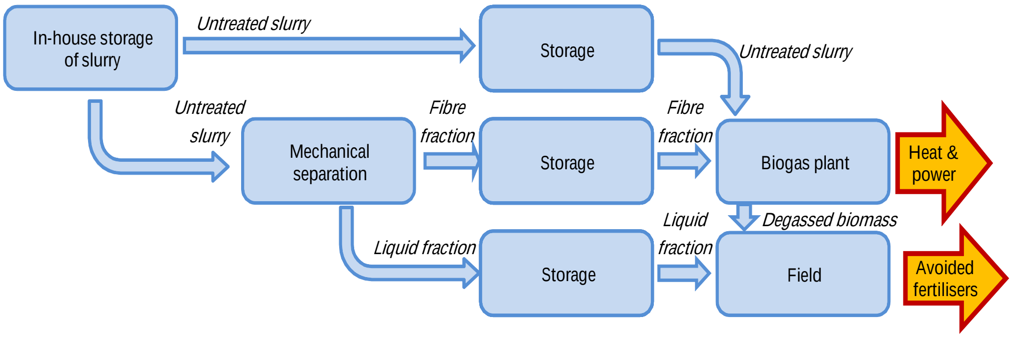
Reference scenario (chapter 3 and Annex A)



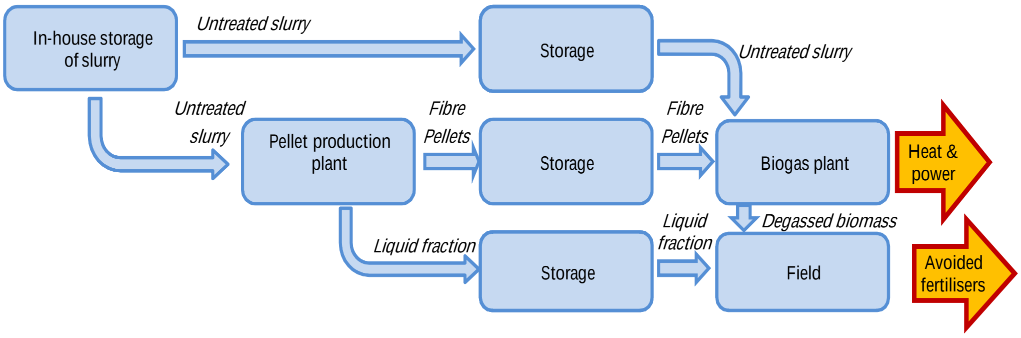
Biogas on separated pig slurry - fibre fraction from mechanical-chemical separation (chapter 4 and Annex F)
AND
Biogas on separated dairy cow slurry - fibre fraction from mechanical-chemical separation (chapter 5 and Annex G)



Biogas on separated pig slurry - fibre fraction from mechanical separation (chapter 6 and Annex H)



Biogas on separated pig slurry - fibre pellets used for biogas production (chapter 7 and Annex I)



2.3 Consequential approach

As in the first publication of this LCA foundation for slurry management technologies, the modelling approach adopted in this LCA study is the consequential LCA approach. Comprehensive details about this methodology can be found in Wenzel (1998), Ekvall and Weidema (2004) and Weidema (2004).

The consequential modelling approach is set up in order to ensure that the results reflect the environmental consequences of implementing a given technology, product or service as compared to the implementation of a given reference scenario. Since the present study aims to highlight the environmental consequences of implementing different biogas technologies for slurry management instead of the conventional slurry management practices (described in section 2.2.1), the consequential approach was the most appropriate.

In the consequential approach, system delimitation requires to include marginal data only (instead of averaged data). In fact, the approach considers that the interactions, i.e the changes in demand, created on the global market as a result of the implementation of a given scenario is the very starting point for the resulting environmental consequences. This means that the marginal processes and activities involved in the system assessed must be identified (i.e. those affected by a change of demand). This can be done in accordance with the methodology and principles described by Weidema (2003) and by Ekvall and Weidema (2004), which can be summarised by the following general principles:

- If the trend for the process or activity of interest is rising, the marginal process or activity is the most competitive one and has the lowest long-term costs;
- If the trend for the process or activity of interest is declining, the marginal process or activity is the least competitive one and has the highest short-term costs.

In the case of the present study, this means that the marginal processes need to be identified for: electricity production, heat production and fertiliser-type (for N, P and K fertilisers), among others. This was performed in Wesnæs et al. (2009). Table 2.1 present the marginal electricity, heat and inorganic fertilisers (N, P and K) used in this study. For heat and electricity, sensitivity analysis was performed with other processes, as elaborated in section 8 of this report.

Table 2.1.
Marginal electricity, heat and inorganic fertilisers (N, P and K) used in this study

Marginal process	Description
Electricity	Mix electricity marginal, based on energy system analysis: 1% wind, 51% Power Plant (coal), 43% Power Plant (natural gas) and 5% electric boiler. Further described in section F.17 of Annex F.
Heat	100 % coal
Inorganic fertiliser - N	Ammonium nitrate, as N. Further described in section A.6.3 of Annex A of Wesnæs et al. (2009).
Inorganic fertiliser - P	Triple superphosphate, as P_2O_5. Further described in section A.6.4 of Annex A of Wesnæs et al. (2009).
Inorganic fertiliser - K	Potassium chloride, as K_2O. Further described in section A.6.5 of Annex A of Wesnæs et al. (2009).

Moreover, the consequential approach ensures system equivalency through system expansion (thereby avoiding any allocation). This is in conformity with the ISO standards (ISO, 2006a; ISO 2006b) which state that “whenever possible, allocation should be avoided”. Interactions from secondary services (i.e. those arising together with the studied service) on the global market are included in the model so the full consequences of the system assessed can be reflected by the model results. As stated in Wesnæs et al. (2009), equivalence on all primary and secondary services is ensured in the consequential approach by identifying and including the displacements of alternative products that will occur when choosing one alternative over the other.

2.4 Basis for the comparison: The functional unit

In order to make a reliable comparison between the different alternatives, it has to be ensured that all alternatives are comparable in terms of the main services provided to society. In order to do so, a functional unit has to be defined (ISO 2006a; ISO 2006b), which shall reflects all services provided. According to ISO (2006a), a functional unit provides “a reference to which the input and output data are normalized”.

In the present study, the functional unit was defined as in Wesnæs et al. (2009), i.e. “Managing 1000 kg slurry”.

All inputs and outputs must then be linked to this functional unit through a reference flow. In the present study, the same reference flow as in Wesnæs et al. (2009) is used, i.e.: “1000 kg slurry ex-animal”.

The functional unit and reference flow are the same as in Wesnæs et al. (2009) as the reference scenario (against which all the studied biogas alternatives will be compared) was defined in Wesnæs et al. (2009). This also ensures consistency and comparability of the various studies forming this life cycle foundation of slurry management technologies.

2.5 System boundaries

As stated in the ISO standards (ISO, 2006a), the system boundary determines which unit process shall be included in the LCA.

The system boundary fixed on this study is consistent with the one fixed in Wesnæs et al. (2009). As explained in Wesnæs et al. (2009), the purpose of this study is comparative, i.e. different alternative biogas technologies are compared to a reference scenario. Because the interest of this study lies in the differences between the different alternatives and the reference scenario, the processes common to all the alternative technologies and the reference scenario will not be included within the system boundary. Similarly, all the processes irrelevant for answering the research question of this study (i.e. What are the environmental benefits and disadvantages of introducing slurry management technology X?) were also excluded from the system boundary. Excluded processes are as described in Wesnæs et al. (2009):

- All the processes occurring prior to the slurry excretion, e.g. production of pigs or cattle, production of feed, production of medicine, housing system, etc.;

- The energy consumed from the housing system. This is assumed to be identical among all fattening pigs scenarios and among all dairy cows scenarios and was therefore excluded of the system boundary;
- The gaseous emissions from the animals (e.g. CH_4 through enteric fermentation or CO_2 through respiration) are not included within the system boundary as they are not a result of changed slurry management;
- The capital goods, e.g. processes related to offices maintenance and consumption for the different technologies suppliers, transport of the employees involved in the different scenarios, cafeterias for employees, etc.

Included within the system boundary are all processes related to slurry handling: e.g. slurry storage (in-house, pre-tank, outdoor storage), slurry treatment (separation, biogas production), electricity needed for slurry handling (pumping, stirring, separation, biogas production), transport needed (for slurry transport from farm to biogas plant, or from outdoor storage to fields) and fertilisation operations (slurry application and slurry fate in the soil).

One innovative aspect of this study is the inclusion of carbon sequestration in the modelling and the consideration of biogenic CO_2 emissions. This was also included in Wesnæs et al. (2009). Biogenic carbon is generally neglected in LCA and considered as “neutral” (e.g. Hansen et al., 2006). Yet, Denmark is committed to include carbon changes in cultivated areas in connection to the Kyoto Protocol (Fødevareministeriet, 2008). Moreover, acknowledging that the carbon in the manure comes from feed (i.e. the portion of C ingested through the feed that was not absorbed by the animal and thereby excreted) and acknowledging the environmental importance of the feed production, it appears important to distinguish between the amount of that C that is returned to atmosphere (as CO_2 and CH_4) and sequestrated in the soils and to account for it. This is the only way to account for the benefits of a slurry management allowing greater C sequestration. This cannot be performed if all biogenic C is ignored and considered as “neutral”.

According to Thomson et al. (2009), the assumption of valuing biogenic carbon or not has substantial consequences in environmental assessments, as it can be a crucial factor in determining if the greenhouse gas balance is positive or negative. Moreover, the biogeochemical C cycle is closely related to the N cycle (Nieder and Benbi, 2008), and this interdependence involves interactions that are ignored if the biogenic C is not taken into account. The optimal range of C and N in soil is rather narrow, and so are crops yields below these optimal ranges (Nieder and Benbi, 2008). However, above these ranges, emissions of reactive C and N compounds occur through both the atmosphere (CO_2, N_2O and NO_X) and as discharge to waters (dissolved N and C) (Nieder and Benbi, 2008). In this study, the C/N ratios of the organic fertilisers that are applied to the land differ as a consequence of the different technologies. Therefore, the resulting environmental consequences of this must be reflected through the inclusion of all biogenic C flows in the model.

As explained in Wesnæs et al. (2009), a reference crop rotation for both the fattening pigs farm and the dairy cows farm has been established in order to estimate the ammonia emissions in the period after application in the field (for liquid fractions). However, the life cycle of these crops is not included within the system boundary (e.g. sowing and harvesting operations, tillage, management of the crop residues, etc.), as this is not a consequence of the slurry management. In the case of the scenarios affecting the crop yield, the system was expanded in order to reflect the consequences of an increased yield.

The consequences regarding extended pig or dairy cow production has not been included. According to Danish law, the introduction of separation with high efficiency will allow the farmer to increase the production, i.e. to have more pigs for the same area of land. With the consequential approach that mean, that the extra pig production should be included, and that pig production somewhere else should be subtracted. Introduction of new technology will not make the consumers eat more pig meat, and therefore, the total production of pigs in the world will not be affected, instead, the least competitive pig producer ("the marginal pig producer") somewhere will have to close down the production and the marked share is lost. It has not been possible to include this aspect in the study.

Conformingly with the approach used by Wesnæs et al. (2009), all emissions and flows with significant environmental impacts have to be included in a life cycle assessment. In case of lack of data, estimates have been made rather than leaving gaps. These estimates were then thoroughly justified in the life cycle inventory annexes.

Furthermore, as stated in Wesnæs et al. (2009), all processes "behind" the processes directly assessed are included, e.g. production of diesel for the tractor, extraction of oil and refinery for production of the diesel, production of the tractor itself, production of mineral fertilisers and production of chemicals for these, extraction of minerals for production of these chemicals, electricity needed for this production, etc. The system "behind" the product chain for slurry management is in fact tremendous and comprises hundreds of processes. The inclusion of these processes "behind" is notably eased by the use of the Ecoinvent database, in combination with a LCA software.

The slurry management alternatives investigated in this project involve complex processes exhibiting a high degree of spatial and temporal variability, and this particularly applies for field processes. Yet, life cycle assessment, as defined in the ISO standards (ISO 2006a; ISO 2006b), is not a methodology capable neither suitable for the modelling of dynamic processes. In fact, when performing LCA, dynamic data must be translated into a set of discrete values that are carefully chosen in order to represent the system assessed as accurately as possible. Such "translations" were performed as transparently as possible and all assumptions taken in this context were justified thoroughly.

2.6 Temporal, geographical and technological coverage

The temporal, geographical and technological coverage considered in this study is as in Wesnæs et al. (2009). Therefore, data from the most recent years (for which consistent data were available) were used. It is the intention that data used for this study applies for 2008 and 5-7 years ahead. As some of the alternative technologies represented in this study are fairly new, it is likely that ongoing product development will improve these technologies during the next decade.

This study covers slurry management under Danish conditions (e.g. housing systems, storage facilities, soil types, application methods, energy production and legislation regarding fertilisation and nutrient substitution). Furthermore, the slurry composition varies significantly within the European countries due to differences in on-farm management, e.g. for feeding (Weidema et al., 2008). Accordingly, it is not possible to transfer the results of this study directly to other European countries without adjustments.

For the reference scenario, the technological coverage is based on “average technology” and represents the “state of the year 2008”. The intended technology level for the alternative technologies is “Best available technology” (BAT), as these technologies are representing the future technologies.

2.7 Environmental Impacts and Resources

The impact assessment phase of the life cycle assessment methodology described in section 2.1 consists to relate the substances flow inventory to environmental impact potentials. The ISO standards for life cycle assessment (ISO 2006a; ISO 2006b) requires to clearly specify the impacts categories used for the assessment as well as the characterisation model upon which they are modelled.

The environmental impact categories chosen in this study are the same as used and described in the first publication of this LCA foundation for slurry management technologies (Wesnæs et al., 2009). These are primarily based on the Danish EDIP method. Not all impact categories from the EDIP method were included, as shown in table 2.2.

All the impacts categories included in this study are ***indicators***, i.e. indicators for impacts on human beings and nature. For example, global warming (climate change) is an environmental concern in itself (mid-point); however, the larger concern is usually the subsequent damages to humans, animals and plants (end-point). Global warming has many impacts, for example drought in some areas, extreme weather conditions, flooding and rising sea levels in other areas, all having potential impact on crop yields and availability of food for humans.

The Life Cycle methodology is a general approach focussing on the ***potential*** contributions of substances and emissions from the systems assessed to the environmental impacts, and ***not*** the actual environmental impacts. This is explained in more details by Wenzel et al. (1997).

Accordingly, it is not within the frame of the LCA methodology to include site specific considerations of e.g. nature being particularly sensitive to specific emissions like e.g. ammonia. This is in accordance with both the ISO standards for Life Cycle Assessment (ISO, 2006a; ISO, 2006b) and international consensus, acknowledging that it is in practice impossible to know all reception sites of the various emissions to the environment and all actual exposure pathways of the emitted substances.

From the EDIP method, the following categories have been included:

- ***Global warming*** (climate change). The main contributors are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The results for global warming are presented as global warming (10 years) and global warming (100 years). This is because the CO_2 emissions from field processes were calculated with both an horizon of 10 years and of 100 years. The unit for characterisation is kg CO_2 equivalent.

- ***Acidification***, which occurs as a result of the deposition of acidifying emissions and substances to ecosystems, causes damage to forest, other vegetation and lakes. The primary contributors to acidification are sulphur oxides (SO_2 and SO_3), nitrogen oxides (NO_x) and ammonia (NH_3). For agriculture, ammonia emissions are especially in focus. The unit for characterisation is m^2 unprotected ecosystems.

- ***Eutrophication*** (nutrient enrichment), which causes damage to lakes and coastal marine waters. The Danish Action Plan for the Aquatic Environment III 2005-2015 (Vandmiljøplan III) is established in order to prevent eutrophication. The contributors are potentially all compounds containing nitrogen (N) and phosporus (P) in a form that is biologically available. When assessing the environmental impacts of slurry management, nutrient enrichment is an important impact category to include. In this study, the EDIP impact categories "Aquatic eutrophication (N)" (for ecosystems where N is the limiting factor to biological growth) and "Aquatic eutrophication (P)" (for ecosystems where P is the limiting factor to biological growth) have been included in order to illustrate the differences of the systems on leaching of nitrogen and phosphorous. The EDIP impact category "Terrestrial eutrophication" has not been included (as it generally shows the same tendencies as the category "Acidification" because it is mainly dominated by NH_3 for the scenarios included in this study). The results for "Aquatic eutrophication (N)" are presented as eutrophication N (10 years) and eutrophication N (100 years). This is because the N leaching to soils from field processes were calculated with both an horizon of 10 years and of 100 years. The unit for characterisation is kg N (for "aquatic eutrophication N") and kg P (for "aquatic eutrophication P").

- ***Photochemical ozone formation ("smog")***, which is caused by reactive compounds forming ozone, in the presence of sunlight (and this is why it is called photochemical ozone formation). The concern with this ozone is that it is formed on the lower layer of the atmosphere (troposphere), i.e. at the human breathable level, causing respiratory problems for humans and potentially reducing growth of crops. This ozone is commonly known as "smog" in large cities. The main contributors are nitrogen oxides (NO_x), volatile organic compounds (VOC) (including CH_4[1]) and carbon monoxide (CO). In life cycle assessments, the main contributions normally come from transport and combustion processes. The EDIP 2003 method has two categories for this, focusing on impacts on humans and impacts on vegetation. However, the results for this study are almost identical for the two categories, and accordingly, only the category, namely "Ozone formation, impacts on humans" has been included (representing both). The unit for characterisation is person*ppm*hour (duration a person is exposed above a threshold concentration for chronic effects).

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[1] Methane is a volatile organic compound, but due to its exceptionally long lifetime, a distinction is often made between methane and others VOC (called NMVOC, which stands for non methane volatile organic compounds).

A few categories have been added to the EDIP method:

- ***Respiratory inorganics (particulates)*** are commonly known as small particles or dust that causes respiratory problems (and death) for humans with asthma or respiratory diseases. Especially particles from diesel cars and wood stoves are known as contributors to these particles formation, but ammonia, nitrogen oxides and sulphur dioxide are also included in this category. Airborne ammonia can react with other airborne emissions (e.g. acidic sulphates and nitrates) and forms small particulates that are regarded as harmful to health when inhaled (Hansen et al., 2008; Janzen et al., 1998). In life cycle assessments transport and combustion processes normally contribute significantly to the particulates emissions. As some of the alternative technologies for slurry management in this study may reduce transport needs, as some include combustion processes, and as ammonia from slurry is significant, this category has been included. The category is based on the LCA method Impact 2002+, which is a combination of some of the best European methodologies (Jolliet et al., 2003; Humbert et al. 2005). In the Impact 2002+ method, particulates are assessed according to size (PM_{10} are particulates with a diameter < 10 µm and $PM_{2.5}$ have a diameter < 2.5 µm). The unit for characterisation is kg $PM_{2.5}$ equivalent.

- ***Phosphorus*** (as a resource) has been chosen as a separate impact indicator category in addition to the general resource calculations in the EDIP method. This is because of the rising concern regarding available phosphorus depletion and because recycling of phosphorus is particularly relevant in the present study. Phosphorus is an essential macronutrient for plant growth. In case of depletion, there could be a serious problem for the global food chain as there are no substitutes. Phosphorus is in fact a core component at the basis of life (e.g. ATP and DNA molecules). Steen (1998) estimates that the current economically exploitable phosphate reserves can be depleted within approximately 100 years (within the range of 60-130 years). The significant reduction in the global crop production that would result without phosphorus fertilisation combined with a massive increase in the world population could lead to hunger and starvation. The normalization factor used in this study is based on Nielsen and Wenzel (2005). The unit for characterisation is kg P.

- ***Non-renewable energy resources.*** The consumption of non-renewable energy resources is included as this is an indicator of the energy consumption of the system. The non-renewable energy resources are calculated by use of the LCA method Impact 2002+ (Jolliet et al., 2003; Humbert et al. 2005). It is expressed in “MJ Primary Energy”, using the upper heating value. The unit for characterisation is MJ equivalent.

- ***Carbon stored in the soil.*** This is not included as an impact category, but is calculated and discussed for all scenarios. In fact, through the different scenarios assessed in this study, a certain amount of C ends up to be stored in soils, which means that this C of the system is not emitted as CO_2. The amount of C sequestered in the soil is calculated as the amount of C applied to the field minus the CO_2 losses. Taking into account the molecular ratios, the corresponding amount of CO_2 not emitted can be calculated.

An attempt to include odour as a separate impact indicator category has been made. Odour emissions, the largest public concern in animal production areas (Blanes-Vidal et al., 2009), is the result of a large number of volatiles compounds. As most of these compounds are by-products of the decomposition of animal slurry (Blanes-Vidal et al., 2009), the slurry management system can have an important influence on the odour emissions. In the present study, technologies acknowledged to have a positive effect on odours (e.g. biogas production and separation) are involved.

However, the inclusion of odour in LCA is not simple, and no methodology to include odour in LCA exists. The definition of where the odour measurements should be taken can be discussed. It is probably more the neighbours of the farm that are affected (or bothered) by the odour than the farmer, but the outdoor emissions from housing units to a great degree depend on the distance to the neighbours, the number of animals in the housing units, wind, temperature etc. Furthermore, the odour problem is not "mathematically linear" – an odour of $100*10^6$ OU_E for 5 days might be worse than an odour of $500*10^6$ OU_E for 1 day. The area where the odour is distributed is very significant, too. Moreover, it has been extremely difficult to find data for odour that can be related to "1000 kg slurry" especially for cattle slurry. The high uncertainty and variability of available data related to odour presents a challenge too. It has thus been decided not to include quantitative data on odour for this study, and odour is not included as an impact category in this study. However, as for the first part of this LCA foundation for slurry management, the database has been prepared for including odour at a later stage.

As mentioned in section 2.5, the production of medicine was not included in the system boundary, as it is a process occurring prior to slurry excretion. Yet, the fate of these medicine residues that will end up in the slurry is likely to be influenced by the slurry management technology considered. However, it has not been possible to find adequate quantitative data on these aspects; thus, they were not included. The database for the LCA foundation was however prepared in order to facilitate their inclusions when more information will be available for this. This also applies for possible biological contamination of the slurry as a result of animal diseases, for example.

Some of the separation technologies considered in this study involve the use of cationic polyacrylamide (PAM), a polymer highly resistant to biodegradation. As not enough information was available to assess the exact fate of this polymer in the environment, the "accumulation of polymer in the environment" was considered as a discussion point only rather than as an impact category.

Table 2.2 presents the different impacts categories considered in this study as well as the methodology used to model each impact. In order to ensure transparency, the impacts categories not considered in this study are also mentioned and their omission is justified.

Table 2.2.
Included and excluded impact categories.

Included impact categories	Methodology
Global warming (climate change)	The EDIP 2003 method (Potting et al., 2003; Hauschild and Potting, 2005; Stranddorf et al., 2005)
Acidification	The EDIP 2003 method (Potting et al., 2003; Hauschild and Potting, 2005; Stranddorf et al., 2005)
Aquatic Eutrophication (N)	The EDIP 2003 method (Potting et al., 2003; Hauschild and Potting, 2005; Stranddorf et al., 2005)
Aquatic Eutrophication (P)	The EDIP 2003 method (Potting et al., 2003; Hauschild and Potting, 2005; Stranddorf et al., 2005)
Photochemical ozone formation (“smog”)	The EDIP 2003 method (Potting et al., 2003; Hauschild and Potting, 2005; Stranddorf et al., 2005). Only “Photochemical ozone formation, impacts on humans” has been included (as it represents the impacts on vegetation – the relative results are almost identical for this study).
Respiratory inorganics (particulates)	From the Impact 2002+ method (Jolliet et al., 2003; Humbert et al., 2005). Relevant for transport and combustion processes and relevant with regard to ammonia, see text above.
Non-renewable energy resources	From the Impact 2002+ method (Jolliet et al., 2003; Humbert et al., 2005). The unit is “MJ Primary Energy”, using the upper heating value.
Phosphorus	Chosen as a special resource indicator as the recycling issue of phosphorus is particularly relevant for this project. The normalization factor used is based on Nielsen and Wenzel (2005).
Carbon stored in soil (and not emitted as CO_2)	This is not included as an impact category per se, but it is calculated and discussed for all scenarios. The C stored in soil is translated to the corresponding amount of CO_2 not emitted, see text above.
Impact categories NOT included	**Comments**
Stratospheric Ozone depletion	Considered insignificant in relation to the chain for slurry management.
Terrestrial eutrophication	From the EDIP 2003 method (Potting et al., 2003; Hauschild and Potting, 2005; Stranddorf et al., 2005) – excluded as it generally shows the same tendencies as the category “Acidification” because it is mainly dominated by NH3 for the scenarios included in this study.
Toxicity	Toxicity in the slurry management chain could be relevant regarding hormones, medicine remains, spreading of Cu and Zn and PAM accumulation. However, there are often huge uncertainties related to toxicity data (if data are available at all). Accordingly, it has been decided to include toxicity in the qualitative discussion instead.
Land Occupation	The Impact 2002+ method has included “land occupation” as a category. It is relevant for agricultural products, but it is regarded less relevant for slurry management, as slurry does not “occupy” areas in the same way as buildings, roads and crops.
Waste	In the EDIP method, waste is included as an impact category. “Waste” as separate category is not especially relevant for slurry management and has not been included as a separate indicator in this study.
Accumulation of polyacrylamide (PAM)	Included as a discussion point.
Odour	It has not been possible to include quantitative data for these categories, see text above. However, the database has been prepared for including these categories at a later stage.
Disease / biological contamination: Vira and pathogenic micro-organisms.	
Hormones	
Medicine remains	

Table 2.3 shows the main emissions that contribute to the impact assessment categories mentioned in table 2.1. According to Sleeswijk et al. (2008), for LCA environmental impact categories not related with toxicity, 10 main contributors can be highlighted: CO_2, CH_4, SO_2, NO_X, NH_3, PM_{10}, NMVOC, (H)CFCs emissions to air as well as emissions of N- and P-compounds to fresh water. Nine of these were in fact inventoried in the present study.

In the case of slurry management, one additional major contributor may be added to the list of Sleeswijk et al. (2008), namely N_2O to air, which is a particularly important contributor to the impact category “global warming”.

The emissions in table 2.3 have been included for all the “foreground processes” as far as possible (i.e. for all the processes regarding slurry management for which data have been collected in this study). The “background processes” from the Ecoinvent database contains far more emissions than these.

Table 2.3.
emissions for the “foreground processes” in this study.

Air emissions included in this study	Impact categories affected by the emissions
Carbon dioxide (CO_2)	• Global warming
Carbon monoxide (CO)	• Photochemical ozone formation (“smog”) • Global warming • Respiratory inorganics / Respiratory problems
Methane (CH_4)	• Global warming • Photochemical ozone formation (“smog”)
Non-methane volatile organic compounds (NMVOC)	• Photochemical ozone formation (“smog”)
Ammonia (NH_3-N)	• Acidification • Eutrophication (nutrient enrichment) • Respiratory inorganics /Respiratory problems • (indirectly to Global warming as NH3 gives indirect N2O emissions)
Nitrous oxide (N_2O-N)	• Global warming • Eutrophication (nutrient enrichment)
Nitrogen oxides (NO_x-N) (including NO2 + NO)	• Acidification • Photochemical ozone formation (“smog”) • Eutrophication (nutrient enrichment) • Respiratory inorganics / Respiratory problems • (indirectly to Global warming as NH3 gives indirect N2O emissions)
Nitrogen (N_2-N)	• Included in order to establish mass balances
Particulates (PM_{10} and $PM_{2.5}$)	• Respiratory inorganics / Respiratory problems
Sulphur dioxide (SO_2)	• Acidification • Respiratory inorganics / Respiratory problems
(Hydrogen sulphide (H_2S) – it was the intention to include this. In practise it was not possible to find sufficient data)	• Human toxicity
Included discharges to water	
Leaching of N (nitrogen) compounds	• Eutrophication (nutrient enrichment) • (indirectly to Global warming as leaching gives indirect N2O emissions)
Leaching of P (phosphorous) compounds.	• Eutrophication (nutrient enrichment)
Copper (Cu)	• Aquatic toxicity
Zinc (Zn)	• Aquatic toxicity

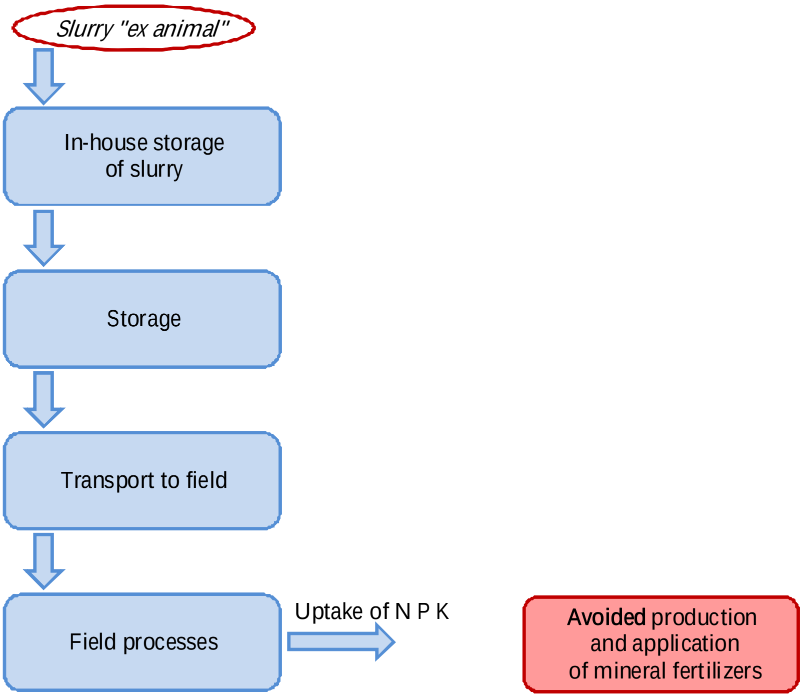
3 Reference scenario for pig and for cow slurry (scenario A)

3.1 System Description

The reference scenario, for both fattening pig and dairy cows, consists to store the slurry in-house, to transfer it to a pre-tank and then to store it in an outdoor storage until application on-field is possible (suitable) (described in section 2.2.1). The final use of the slurry is then as an organic fertiliser. This scenario is thoroughly described in the first part of this LCA foundation for slurry management (section 3 of Wesnæs et al., 2009). All life cycle inventory data used for this reference scenario can be found in Annex A of Wesnæs et al. (2009). The major elements from this can be found in Annex A of the present study.

A simplified diagram illustrating the main processes involved in the reference scenario is presented in figure 3.1 (after Wesnæs et al., 2009).

Figure 3.1.
Simplified flow diagram for the reference scenario (After Wesnæs et al., 2009)



As mentioned in Wesnæs et al. (2009), it has been necessary to define the preconditions concerning the reference scenarios regarding e.g. housing units, type of storage, technology for application to the field and reference cropping scenarios. These pre-conditions also apply for all subsequent alternatives assessed. These pre-conditions are summarised in the present study, but their full description and justification can be found in Wesnæs et al. (2009).

For fattening pigs, these pre-conditions include (after Wesnæs et al., 2009):

- Housing conditions based on a housing system with "***Fully slatted floor"***.
- Pumping of the slurry from the pre-tank (in connection with the housing units) to the outdoor storage.
- Outdoor storage in concrete slurry tanks ***covered by a floating layer*** of straw.
- A ***transport distance*** from storage to application to fields of 10 km.
- Slurry application by ***trail hose tankers.***
- Relevant ***soil types*** for application of pig slurry: soil type JB3 (representing sandy soil) and soil type JB6 (representing clay soil).
- It is assumed that pig slurry is applied to all crops in the crop rotation pattern, with a farm average of 140 kg N ha^{-1} y^{-1}. It is also assumed that the slurry is applied during spring.
- A six year crop rotation, with slurry N (kg ha^{-1} y^{-1}) applied shown in parenthesis: winter barley (133.5) – winter rape (133.5) - winter wheat (133.5) – winter wheat (133.5) – spring barley with catch crop (165) – spring barley (145). As mentioned in section 2, the crops are not included within the system boundaries. They are only defined as the uptake and emissions of N and P in slurry depends on the crop, and in order to model the further fate of the N not removed with harvested products.

For dairy cows, these pre-conditions include (after Wesnæs et al., 2009):

- Housing conditions based on a "Cubicle housing system with slatted floor (1.2 m channel)" [2].
- Pumping of the slurry from the pre-tank (in connection with the housing system) to the outdoor storage.
- Outdoor storage in concrete slurry tanks covered by a ***natural floating layer***.
- A transport distance from storage to application to fields of 10 km.
- Slurry application by ***trail hose tankers***.
- Relevant ***soil types*** for application of pig slurry: soil type JB3 (representing sandy soil) and soil type JB6 (representing clay soil).
- It is assumed that cattle slurry is applied to all crops in the crop rotation pattern, with a farm average of 140 kg N ha^{-1} y^{-1}. It is also assumed that the slurry is applied during spring.
- A five year crop rotation, with slurry N (kg ha^{-1} y^{-1}) applied shown in parenthesis: spring barley harvested as whole crop silage (156) – grass clover mixture (182) – grass clover mixture (182) – spring barley with catch crop (0) – spring barley (132). Besides this, 15 % of the area is assumed utilised for continuous silage maize (188).

3.2 Composition of reference slurry

As described in Wesnæs et al. (2009), the slurry composition is the very basis for the different process flows involved in this LCA foundation. The "reference slurry " upon which all flows of this study will be normalized is defined as " slurry ex-animal", i.e. the slurry produced right after animal excretion. This is chosen as the reference point as this is where the system

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[2] In Danish: Sengestald med spaltegulv (1.2 m kanal)

boundaries start. The composition of the slurry in the reference scenario is calculated at three points:

- Slurry “ex animal”, i.e. right after excretion;
- Slurry “ex housing”, i.e. in the slurry pit under the animals right before flushing to the pre-tank;
- Slurry “ex storage”, i.e. after months of covered outdoor storage, measured right before application to field.

The chemical composition of pig slurry is given in table 3.1. The composition of dairy cow slurry is given in table 3.2. The explanations for the composition are given in Annex A of Wesnæs et al. (2009). The number of digits in table 3.1 and 3.2 should not be seen as a measure of the precision, but is only included as the values are the foundation for further calculations.

Table 3.1.
Characteristics of slurry from fattening pigs in the reference scenario. Per 1000 kg of slurry “ex animal”, “ex housing” and “ex storage”. (after Wesnæs et al., 2009)

	Ex Animal	Ex housing	Ex storage
Total mass	1000 kg Slurry ex animal	1000 kg Slurry ex housing	1000 kg Slurry ex storage
Dry matter (DM)	77.4 kg	69.7 kg	61 kg
Ash content	13.2 kg	13.2 kg	12.2 kg
Volatile solids (VS)	64.2 kg	56.5 kg	48.8 kg
Of total VS:			
- easily degradable	41.7 kg	34.0 kg	28.1 kg
- heavily degradable	22.5 kg	22.5 kg	20.7 kg
Total-N (Norm Data, DJF, 2008)	*6.60 kg*	*5.54 kg*	*5.00 kg*
Total-N in this study	6.60 kg	5.48 kg	4.80 kg
NH4^{+}-N	No data	No data	3.60 kg
Total-P	1.13 kg	1.13 kg	1.04 kg
Potassium (K)	2.85 kg	2.85 kg	2.60 kg
Carbon (C)	37.0 kg	33.3 kg	29.2 kg
Copper (Cu)	30.0 g	30.0 g	27.6 g
Zinc (Zn)	89.4 g	89.4 g	82.4 g
Density	1053 kg per m^3	1053 kg per m^3	1053 kg per m^3
pH	7.8	7.8	7.8

Table 3.2.
Characteristics of slurry from dairy cows in the reference scenario. Per 1000 kg of slurry “ex animal”, “ex housing” and “ex storage”. (after Wesnæs et al., 2009, with corrections of the units for Cu and Zn)

	Ex Animal	Ex housing	Ex storage
Total mass	1000 kg slurry ”ex animal”	1000 kg slurry ”ex housing”	1000 kg slurry ”ex storage”
Dry matter (DM)	125.7 kg	113.2 kg	103 kg
Ash content	21.5 kg	21.5 kg	20.6 kg
Volatile solids (VS)	104.2 kg	91.7 kg	82.4 kg
Of total VS:			
- easily degradable	50.0 kg	37.5 kg	30.5 kg
- heavily degradable	54.2 kg	54.2 kg	51.9 kg
Total-N (Norm Data, DJF, 2008)	*6.87 kg*	*6.41 kg*	*6.02 kg*
Total-N in this study	6.87 kg	6.34 kg	5.79 kg
$NH4^+$-N	No data	No data	3.47 kg
Total-P	1.02 kg	1.03 kg	0.98 kg
Potassium (K)	5.81 kg	5.90 kg	5.65 kg
Carbon (C)	55.2 kg	49.7 kg	45.2 kg
Copper (Cu)	12.1 g	12.1 g	11.6 g
Zinc (Zn)	23.4 g	23.4 g	22.4 g
Density	1053 kg per m^3	1053 kg per m^3	1053 kg per m^3
pH	7.8	7.8	7.8

3.3 Data for the reference scenarios

All data for the references scenarios are presented in Annex A of Wesnæs et al. (2009) and summarised in Annex A of the present study.

3.4 Results of the Impact Assessment

The results of the impact assessment for the reference scenario are presented and discussed in detail in Wesnæs et al. (2009). In the present study, the results of all assessed scenarios are compared to the results for the reference scenario, as presented in the next sections.

4 Biogas production from raw pig slurry and fibre fraction from mechanical-chemical separation (Scenario F) – results and interpretation

This section presents the results and the interpretation from the life cycle assessment carried out for “Scenario F”, described below. The results from “Scenario F” are compared to those of the reference scenario for fattening pig slurry management, i.e. “Scenario A”. Doing so, it is therefore possible to answer the research question: ***“What are the environmental benefits and disadvantages of producing biogas from raw pig slurry and the fibre fraction obtained from a mechanical-chemical separation process, as compared to the reference situation for pig slurry management?”***

Scenario F was built in such a way that it integrates the “best available technologies” as well as the “best possible practices” as much as possible for an optimal environmental performance. This is important to remember in the results interpretation.

The detailed description of this scenario, including all mass balances, assumptions and calculations, is presented in Annex F. All life cycle inventory data used for the results presented in this section can therefore be found in Annex F.

4.1 System description

The system constituting Scenario F, as described in section 2.2.2, consists to produce biogas from a mixture of fibre fraction (from mechanically separated slurry, flocculated with polymer) and raw slurry, both from fattening pigs. After excretion (1000 kg), raw slurry is stored in-house; part of it is separated (845.1 kg) and part of it is kept as raw slurry (154.9 kg). These fractions do not necessarily come from the same farm (and most probably they do not), but they both end up at the biogas plant. Once at the biogas plant, these fractions are mixed according to their composition and to their degradability in order to achieve realistic production conditions. The separation process used is considered as a “best available technology” as regarding its efficiency to increase the relative fraction of dry matter and nutrients transferred to the fibre fraction. While the separated liquid fraction (651.9 kg) is stored and used on-field as an organic fertiliser, the separated fibre fraction (193.2 kg), as well as the raw slurry, is used as an input for biogas production. The temporal storage of the fibre fraction before the fibre is used for biogas production is assumed to be rather short (range of 1 to 3 days with 7 days as a maximum), which is considered as a “best management practice”. Similarly, it has been assumed that the raw slurry is stored in the pre-tank for a duration of less than

14 days before it is transferred either to the biogas plant or to the separation process, which is also considered as a “best management practice”.

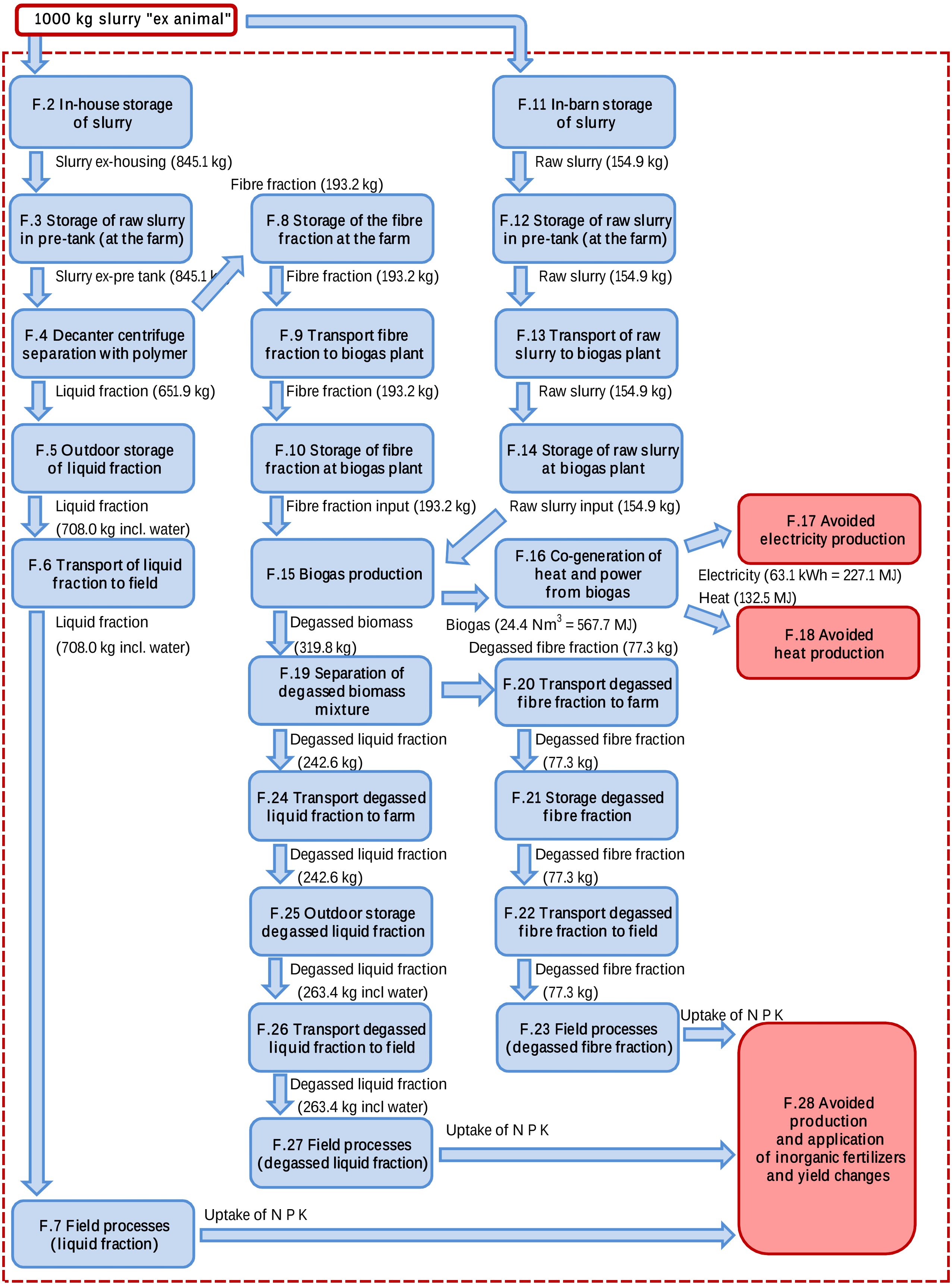
The biogas produced (24.4 Nm^3) from the raw slurry and the fibre fraction mixture is used for co-production of heat and power, but a sensitivity analysis assesses the impacts of using the biogas directly as a source of natural gas (injected in the natural gas grid). The biogas engine used for the generation of heat and power is also considered as a “best available technology”, as the engine used has conversion efficiencies ranking in the highest available range.

After the anaerobic digestion, the resulting degassed biomass (319.8 kg) is mechanically separated, but without polymer addition. The degassed liquid fraction resulting from this separation process (242.6 kg) is then stored until it can be used on-field as a fertiliser. The resulting degassed fibre fraction (77.3 kg) is stored as air-tight covered heap, the heaps being covered by a polyethylene plastic sheet. Others options are available for the management of the degassed fibre fraction (e.g. processing it in order to make fibre pellets), but covering was considered as a “best available technology”, as explained in Annex F (section F.21.1).

The processes described and used for this scenario were built in collaboration with Xergi A/S and some of the data used were obtained directly from Xergi A/S (see Annex F). The conclusions made in this section rely on this information, and the authors of this study have not had the possibility of verifying these data.

Figure 4.1 presents the process flow diagram for “Scenario F”. The process numbers in figure 4.1 follows the numbers of the sections in Annex F.

Figure 4.1.
Process flow diagram for “scenario F” – Biogas from raw pig slurry and fibre fraction of mechanical-chemical separation of pig slurry. The process numbers follows the numbers of the sections in annex F.



4.2 Results of the Impact Assessment

4.2.1 Overall results of the comparison

Table 4.1 presents the results of the overall environmental impacts from “Scenario F” (biogas from raw pig slurry and fibre fraction from mechanical-chemical separation), and compare them to the impacts from the reference scenario “Scenario A” (described in section 3). Figures 4.2 A and 4.2.B illustrate the results presented in table 4.1. Figures 4.2 A and 4.2.B are identical except for the minimum and maximum at the axis. In the case of figure 4.2.B, the minimum and maximum were adjusted in order to present the full impacts covered for the consumption of non-renewable energy impact category. Results are presented for soil JB3 only (sandy soil). A sensitivity analysis assesses the differences in the results that are obtained if another soil type (soil JB6: clay soil) is considered (see section 8).

The results presented are “characterised” results (as described in section 2.1). In the present case, the results are expressed relative to the result of the reference scenario for each impact category. The positive values are the contributions to the environmental impacts and resource consumptions by the slurry management scenarios. The negative values are “avoided environmental impacts”, because the production and/or consumption of a given good or service is avoided, or rather, it is replaced (and therefore subtracted from the system). For example, when electricity is produced from biogas, it replaces electricity production somewhere else, and hence, this is avoided – and subtracted from the system. In scenario F, G, H and I, the system obtains deductions for the heat and electricity production (as heat and electricity is produced from the biogas), for the “fertiliser value” of the slurry (the liquid fraction and the degassed fractions, see section F.28) and for extra crop yield, as the degassed fractions provides a higher fertiliser value (this is further explained in section F.28).

In order to calculate the results of table 4.1 (and figures 4.2 A and B), the sum of the positive contributions of each process of the reference scenario was, for each impact category, equated to 100 %. The contributions to a given impact category from scenario F could then be expressed as a percentage of the total contribution in the reference scenarios. This is illustrated by equation 4.1:

$$\text{Relative contribution (\%)} = \frac{(\text{Contribution from process i})_{cat} * 100\ \%}{(\text{Sum of positive contributions from reference scenario A})_{cat}} \qquad \text{(Eq. 4.1)}$$

Where ***cat*** is the environmental impact category concerned (e.g. global warming, acidification, etc.). The sum of positive contributions is with the 10 years values for C horizon in the field, when this applies. This involves, as presented in Wesnæs et al. (2009), that the environmental impacts with the 100 years values (global warming and eutrophication -N) are above 100 % for the reference scenario.

Results presented in table 4.1 should be interpreted with care in the light of the assumptions and data that were used to obtain them, i.e. the life cycle inventory data presented in Annex F. An attempt to discuss these results based on this focus, impact category per impact category, is presented in sections 4.2.2 to 4.2.11.

Table 4.1.

Scenario F vs A: Contribution of the different processes to each environmental impact categories selected. Results, for each impact category, are expressed in % of the total positive contributions from the reference scenario (considering the 10 years values, when this applies). Soil JB3 (sandy).[1]

Impact Categories	GW (10 y)	GW (100 y)	Acidification	Eutrophication (N) (10 y)	Eutrophication (N) (100 y)	Eutrophication (P)	Ozone formation	Respiratory inorganics	Non-renewable energy	Phosphorus resources
SCENARIO A – pig										
A.2 In-house storage	31.7	31.7	60.0	16.3	16.3	0.0	56.2	56.2	0.0	0.0
A.3 Outdoor storage - elect	1.4	1.4	0.3	0.0[a]	0.0[a]	0.0[a]	0.5	0.4	37.0	0.0[a]
A.3 Outdoor storage	21.4	21.4	8.0	2.4	2.4	0.0	38.7	10.4	0.0	0.0
A.4 Transport to field	1.2	1.2	0.6	0.2	0.2	1.1	1.8	2.5	36.8	0.0[a]
A.5 Field processes	44.3	51.2	31.1	81.1	89.1	98.8	2.8	30.5	26.2	0.0[a]
A.6 N fertiliser	-10.6	-14.3	-7.9	-61.1	-67.7	-1.8	-5.8	-12.1	-170.1	0.0[a]
A.6 P fertiliser	-1.5	-1.5	-2.8	-0.1	-0.1	-121.8	-1.3	-4.5	-51.2	-99.9
A.6 K fertiliser	-0.6	-0.6	-0.2	0.0[a]	0.0[a]	-0.5	-0.6	-0.7	-22.2	-0.1
Sum of positive contributions	***100***	***107***	***100***	***100***	***108***	***100***	***100***	***100***	***100***	***0.0***[a]
Sum of negative contributions	***-13***	***-16***	***-11***	***-61***	***-68***	***-124***	***-8***	***-17***	***-244***	***-100***
SCENARIO F										
F.2 + F.11 In-house storage	31.7	31.7	60.0	16.3	16.3	0.0	56.2	56.2	0.0	0.0
F.3 + F.12 Pre-tank storage	0.5	0.5	0.1	0.0[a]	0.0[a]	0.0[a]	0.2	0.1	12.6	0.0[a]
F.4 Separation – elect & equipment	0.5	0.5	0.1	0.0[a]	0.0[a]	0.1	0.2	0.2	14.0	0.0[a]
F.4 Polymer for separation	0.2	0.2	0.1	0.0[a]	0.0[a]	0.1	0.2	0.1	10.4	0.0[a]
F.5 Outdoor storage liquid fraction	4.6	4.6	4.0	1.2	1.2	0.0[a]	6.6	5.2	7.0	0.0[a]
Transport (F.6, F.9, F.13, F.20, F.22, F.24, F.26)	1.6	1.6	0.8	0.2	0.2	1.2	2.5	3.0	51.0	0.0[a]
F.7 Field processes (liquid fraction)	7.2	9.8	8.5	38.3	42.3	8.7	1.6	9.0	17.1	0.0[a]
F.8 Storage fibre fraction on-farm	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.1	0.0[a]
F.10 Storage fibre fraction biogas pl.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
F.14 Storage raw slurry biogas plant	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
F.15 Biogas production	1.9	1.9	0.2	0.0[a]	0.0[a]	0.0[a]	2.2	0.3	23.5	0.0[a]
F.16 Co-generation heat and power	18.4	18.4	5.8	1.9	1.9	0.1	24.2	14.1	3.6	0.0[a]
F.17 Avoided electricity production	-18.1	-18.1	-3.3	-0.3	-0.3	-0.6	-6.8	-4.9	-471.9	0.0[a]
F.18 Avoided heat production	-6.1	-6.1	-4.7	-0.3	-0.3	-0.8	-3.6	-6.2	-114.1	0.0[a]
F.19 Separation degassed mixture	0.2	0.2	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.1	0.1	5.3	0.0[a]
F.21 Storage degassed fibre fraction	0.6	0.6	4.3	1.2	1.2	0.0[a]	0.4	4.0	0.3	0.0[a]
F.23 Field processes (degassed fibre fraction)	10.8	13.1	2.4	4.8	8.9	59.6	0.3	2.4	2.7	0.0[a]
F.25 Outdoor storage (degassed liquid fraction)	2.9	2.9	2.9	0.8	0.8	0.0[a]	4.4	3.4	2.6	0.0[a]
F.27 Field processes (degassed liquid fraction)	7.9	10.3	13.5	32.2	35.4	30.6	2.3	13.5	6.4	0.0[a]
F.28 N fertiliser – production & application on JB3	-10.6	-14.3	-7.9	-61.1	-67.7	-1.8	-5.8	-12.1	-170.1	0.0[a]
F.28 P fertiliser – production & application on JB3	-1.8	-1.8	-3.4	-0.1	-0.1	-150.3	-1.7	-5.6	-63.2	-123.3
F.28 K fertiliser – production & application on JB3	-0.7	-0.7	-0.2	0.0[a]	0.0[a]	-0.6	-0.6	-0.7	-23.2	-0.1
F.28 Yield changes	-0.9	-1.3	-0.7	-3.6	-4.9	-2.4	-0.5	-0.9	-8.4	-1.3
Sum of positive contributions	***89***	***96***	***103***	***97***	***108***	***100***	***101***	***112***	***157***	***0.0***[a]
Sum of negative contributions	***-38***	***-42***	***-20***	***-65***	***-73***	***-156***	***-19***	***-30***	***-851***	***-125***

[1] The number of digits is *not* an expression of the uncertainty. All numbers are all rounded and accordingly, if the reader calculates the sum or the difference, it might vary slightly from the numbers shown in the table.

[a] This number is not a zero value.

Figure 4.2.a

Overall environmental impacts for the selected impact categories – scenario F vs scenario A. Fattening pig slurry management. Soil type JB3. 10 and 100 years time horizon for global warming and for aquatic eutrophication (N). **Axis ranging from -180 to 120.**

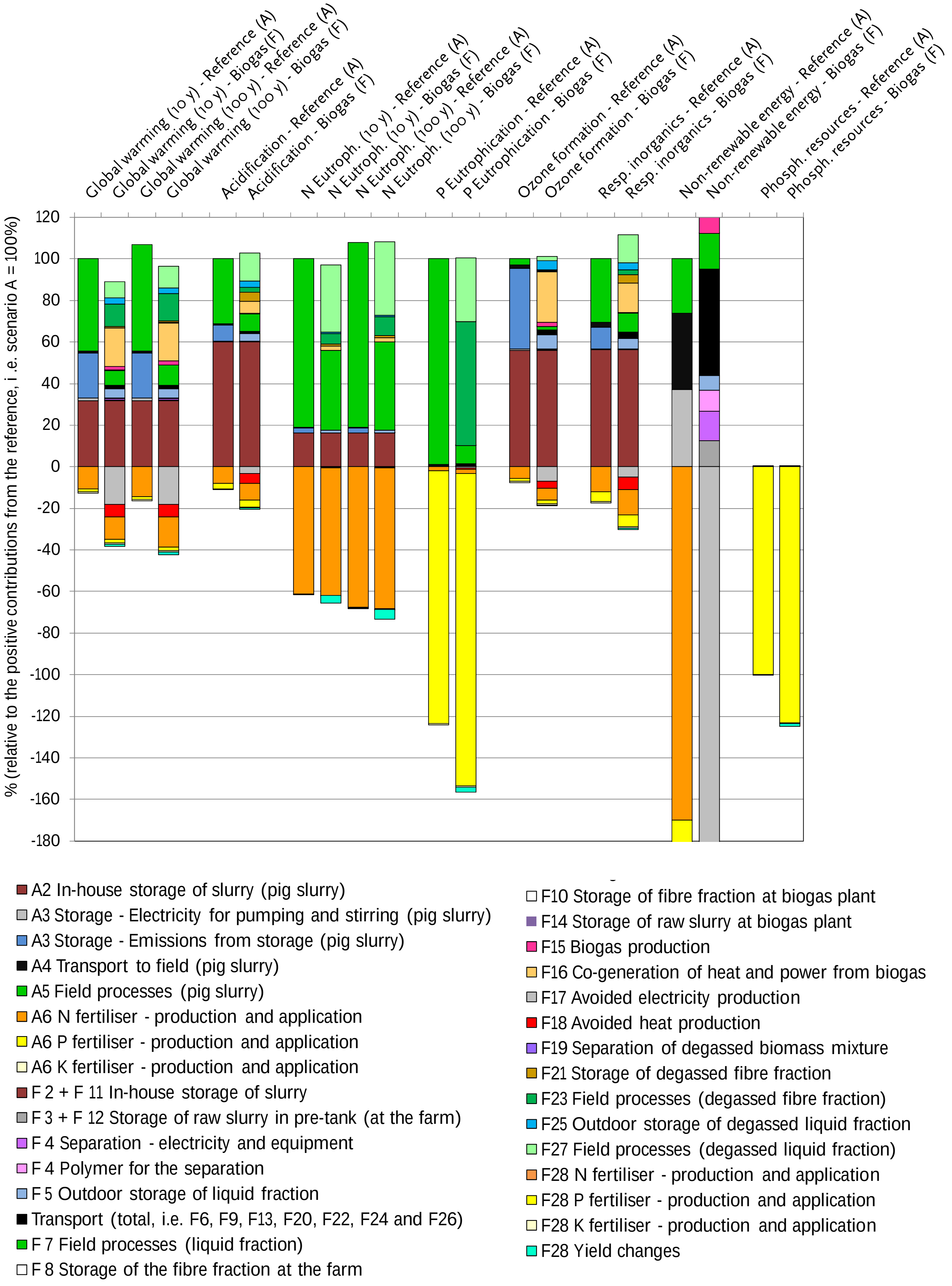
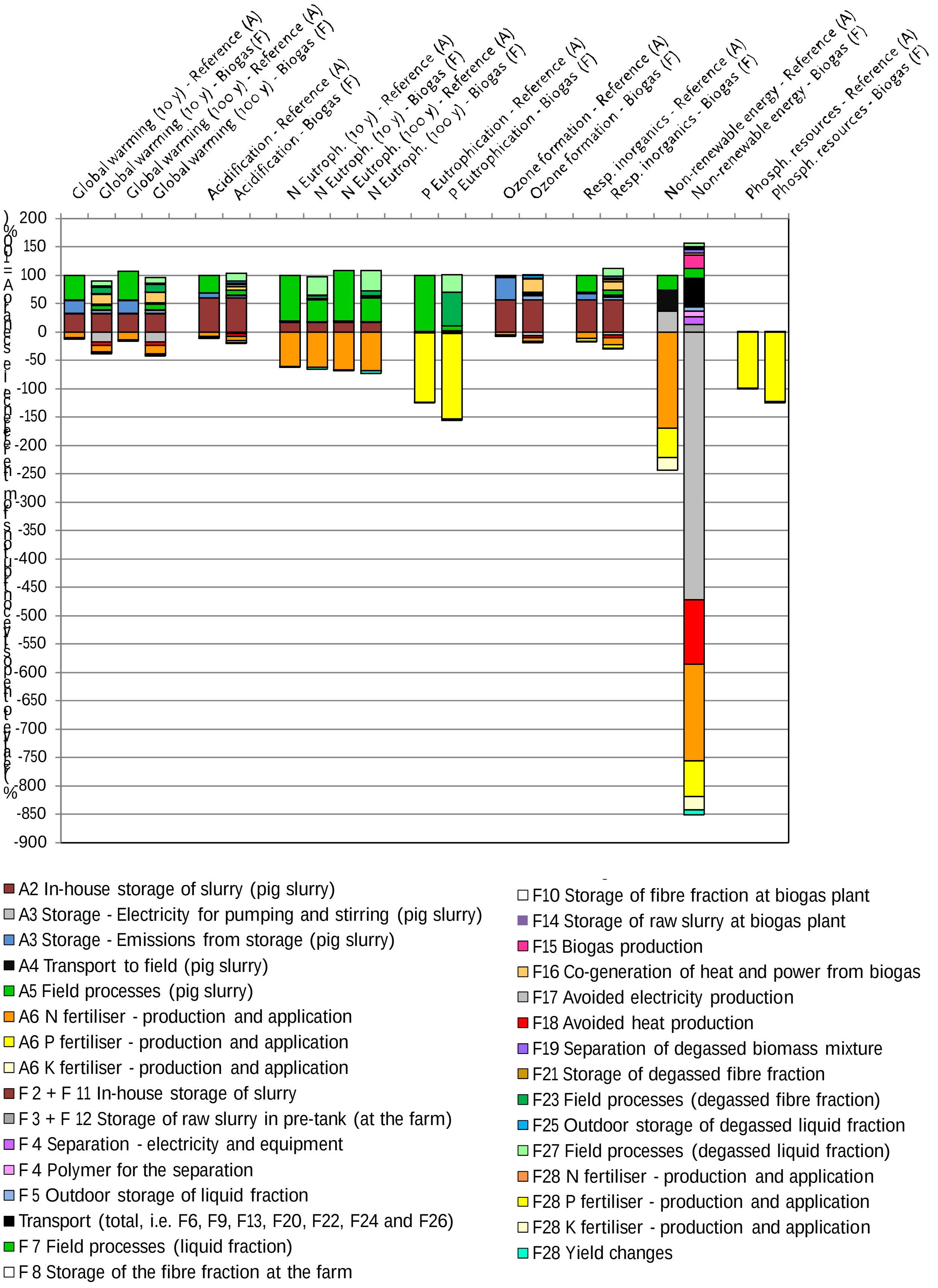


Figure 4.2.b
Overall environmental impacts for the selected impact categories – scenario F vs scenario A. Fattening pig slurry management. Soil type JB3. 10 and 100 years time horizon for global warming and for aquatic eutrophication (N). Axis ranging from -900 to 200.



In the following sections, the benefits (and shortcomings) of producing biogas as described in Scenario F instead of the reference slurry management are discussed in details for each impact categories.

Sensitivity analyses were performed for some processes, as described in Annex F. The results of these sensitivity analyses are presented in section 8 of this report.

4.2.2 Global warming

Different trends can be observed from figure 4.2.A as regarding global warming.

First, when analysing the positive contributions, it can be seen that there are two major hot spots to global warming contribution:

- In-house storage of slurry
    - Scenario A and F: This process represents 32 % of the total positive contributions to global warming from the reference scenario.
- Field processes
    - Scenario A: This process represents 44 % of the total positive contributions to global warming from the reference scenario (and 51 % if the 100 years values are considered for C horizon in the field).
    - Scenario F: This process (for the aggregation of all organic fertilisers: liquid fraction, degassed fibre fraction and degassed liquid fraction) represents 26 % of the total positive contributions to global warming from the reference scenario (and 33 % if the 100 years values are considered for C horizon in the field).

The significant contribution from the in-house storage is due to CH_4 emissions (for which, in the EDIP method, the 100 years global warming potential is 23 g CO_2 equivalents per g CH_4. This in turn is based on IPCC, 2001). In fact, only three gases contribute to the global warming potential of this process: CH_4 (84 %), N_2O (12 %) and CO_2 (4 %). The proportions shown in parenthesis are for a 10-years value as regarding the C horizon in the field.

High emissions from CH_4 were expected for this process, as the anaerobic conditions for slurry stored below animal floors favour CH_4 formation more than the formation of other greenhouse gases (i.e. those contributing to the global warming impact category). Yet, the high absolute contribution from CH_4 is due to a conservative methodological choice. As detailed in Annex F (section F.2), CH_4 is estimated based on IPCC methodology. This methodology involves a parameter called “methane conversion factor” (MCF: see definition in Annex F, section F.2), which range between 0 % (no methane formation) to 100 % (all methane producing potential is achieved). To ensure system equivalency, this parameter needs to be the same for the reference scenario (Scenario A) and the present scenario (Scenario F), as the in-house management of the slurry is performed the same way in both scenarios. Yet, a MCF of 17 % was used to build the reference scenario in the first part of this project (Wesnæs et al., 2009). This comes from tabulated values provided by the IPCC (IPCC, 2006) and corresponds to the value for pit storage below animal confinement greater than 1 month (table 10.17 in IPCC, 2006). The alternative value that could have been used for calculating in-house CH_4 emissions is a MCF of 3 %, for an in-house storage duration below one month. Doing so, the emissions from CH_4 from in-house storage would have been 0.58 kg CH_4 per 1000 kg slurry ex-animal (instead of the 3.29 kg of table F.1, Annex F). Considering a factor of 23 kg CO_2 equivalent/kg CH_4 (EDIP method, for global warming on a 100 years horizon), a MCF of 3 % would therefore gives a reduction of 62.3 kg CO_2 equivalent for this process. This corresponds to a reduction of 69 % of the global warming potential for this process as compared to what it is in this study (90.27 kg CO_2 equivalent), which is rather significant. The CH_4 would still have had the highest share in terms of contribution to the global warming potential from this process (CH_4: 38 %; N_2O: 32 % and CO_2: 31 %). However, as explained in Annex F, this conservative estimation does not affect the conclusions to be drawn from this project, as the in-house storage is identical for all scenarios assessed. It may only overestimate the impact of in-house storage as a process contributing to the global warming potential in the scenarios assessed. With a MCF of 3 %, field processes would have been the major hot spot for global warming together with co-generation of heat and power.

For both Scenario F and A, the contribution of field processes to global warming potential is dominated by biogenic CO_2 (due to C from applied slurry being emitted as CO_2). In the case of Scenario F, biogenic CO_2 represents 60 % of the contribution to global warming from field processes, while N_2O represents 37 % and fossil CO_2 emissions (due to diesel combustion) represents 3%. In fact, there are other gases involved, but their relative contribution is rather insignificant (and not reflected when the percentages are expressed with no decimal place). The biogenic CO_2 emitted in the field is lower for Scenario F than Scenario A (44 kg CO_2 equivalent in Scenario F as compared to 89 kg CO_2 equivalent in Scenario A). This is simply because, in the case of Scenario F, this biogenic CO_2 was emitted in earlier stages, mostly during the co-generation of heat and power. In that case, however, heat and electricity were produced together with the emission.

For Scenario F, it can also be highlighted that the biogenic CO_2 emissions from field processes are the highest with the application of the degassed fibre fraction (27 kg CO_2equivalent) as compared to the degassed liquid fraction (14 kg CO_2equivalent) and the liquid fraction (3 kg CO_2equivalent), respectively. This is because the fibre fraction has the highest C content per functional unit (table 4.2), and because it was considered that, on both a 10 and a 100 years horizon for C, most of the “slowly degradable” portion of the C end up to be degraded, thus contributing to CO_2 emissions.

High contributions to global warming potential from N_2O were expected for field processes, because N_2O has a 100-years global warming potential of 296 kg CO_2 equivalent per kg N_2O, based on the EDIP method (which in turn is based on IPCC, 2001). In Scenario F, “field processes” consist of: the application of separated liquid fraction to field (process F.7, see Annex F), the application of degassed solid fraction to field (process F.23, see Annex F) and the application of degassed liquid fraction to field (process F.27, see Annex F). In all these, the emission of N_2O were estimated based on the IPCC methodology (IPCC, 2006), accordingly, the emissions are estimated as a function of the N content in the applied slurry. Table 4.2 shows the C and N content of the different fractions involved in scenario A and F.

Table 4.2.
C and N content of the different organic fractions involved in Scenario A and F

Material	Amount per functional unit (kg)	N in material (kg)	C in material (kg)	C/N	N per functional unit	C per functional unit
Scenario F						
Liquid fraction	708.0	3.61	4.8	1.33	2.56	3.40
Degassed fibre fraction	77.3	6.64	126.92	19.11	0.51	9.81
Degassed liquid fraction	263.4	8.03	23.72	2.95	2.11	6.24
Scenario A - pig						
Slurry ex-storage	1086	4.8	29.2	6.08	5.21	31.71

The separated liquid fraction thus has the highest contribution to N_2O (as it has the highest N content per 1000 kg slurry ex-animal), followed by the degassed liquid and the degassed fibre fraction. The contribution of N_2O to global warming from field processes has a similar magnitude in both Scenarios A and F (27 kg CO_2 equivalent in Scenario F and 35 kg CO_2 equivalent in Scenario A). If the emissions of N_2O-N represent 3 to 5 % of the N applied as suggested by Crutzen et al. (2008) rather than the 1 % of the IPCC methodology (IPCC, 2006) as used in this study, the global warming contribution from field processes would be much more important, as a small increment of N_2O has huge impact on global warming potential.

The co-generation of heat and power from biogas also represents a rather significant contribution to global warming, representing 18 % of the total positive contributions to global warming from the reference scenario. This, as it can be deduced from table F.24 of Annex F, is mainly due to the combustion gases from burning the biogas (i.e. CH_4 and CO_2) in the biogas engine. The production of biogas itself (process F.15 of Annex F) represents a minor share of the contribution to global warming potential, with only 2 % of the total positive contributions to global warming from the reference scenario. The contribution to global warming from the biogas production process is due to fossil CO_2 associated with the electricity input (44 %) as well as to the methane leaching (49 %).

Another interesting observation to highlight from figure 4.2.A is the benefit on global warming contribution of storing the slurry as separated (and degassed) fractions rather than as raw slurry. While storage of raw slurry represents 21 % of the total positive contributions to global warming from the reference scenario, the contribution from separated liquid is 4.6 %, and it is 0.6 % and 2.9 % for the degassed fibre fraction and the degassed liquid fraction, respectively. This is mainly because of lower CH_4 emissions. Emissions of CH_4 are lower with separated liquid slurry as most of the DM, and thereby the VS, are transferred to the solid fraction (it is from the anaerobic degradation of the VS that CH_4 is produced during storage of slurry). Yet, two types of VS can be distinguished, those that degraded easily and those that are recalcitrant to microbial degradation. Due to a lack of data, it was assumed that all the VS in the separated liquid fraction are easily degradable VS, which in fact may not be the case. In such a case, then the CH_4 emissions from the stored liquid fraction would be even lower than estimated in the present project, as further explained in section F.5.4 of Annex F. This also applies for N_2O, as described in section F.5.7 of Annex F.

For the degassed fractions (liquid and fibre), the CH_4 emissions are reduced as most of the VS easily degradable were degraded during the anaerobic digestion, only leaving a small emission potential for further CH_4 emissions in the subsequent storage of the fractions.

Finally, as it can be observed from figure 4.2.A, the contribution to global warming from the use of electricity, the use of polymer for separation and the transportation are rather negligible for the assessed scenarios.

Both slurry management assessed allow avoiding the use of inorganic fertilisers (N, P and K). Furthermore, the biogas scenario allows avoiding the production of marginal heat and electricity (see definition section 2.3). Avoiding the production of marginal electricity (a mix of wind, coal and natural gas, see table 2.1) by the use of the electricity produced from the biogas allow considerable benefits in terms of global warming contribution avoided. This corresponds to an “avoidance” of 18 % of the total positive contributions to global warming from the reference scenario. Avoiding the production of marginal heat (i.e. 100 % coal, see table 2.1) through the heat produced from the biogas also has also a positive impact on global warming contribution (an avoidance of 6 % of the total positive contributions to global warming from the reference scenario). In section 8, a sensitivity analysis was carried out in order to assess the impact of changing the marginal electricity and heat source replaced. This illustrates how the gain from the biogas production can be greater if the energy source replaced has a greater contribution to the global warming, and vice versa.

Avoiding the production and use of inorganic fertilisers (particularly N, but also P and K to a lesser extent) through the use of the produced organic fertilisers contribute, for both Scenario A and Scenario F, to the avoidance of global warming potential, and this avoidance is in the same order of magnitude for both scenarios. Avoiding the production and use of inorganic N avoids the production of N_2O which represents the main reason for the magnitude of avoided contribution to global warming for this process. As explained in Annex F (section F.28.2), the amount of N avoided is the same in Scenario F than in the reference scenario as the “rule of conservation” (Gødskningsbekendtgørelsen, 2008) was applied to calculate the amount of inorganic N substituted by each organic fractions. The amount of inorganic P and K substituted in Scenarios A and F are different, but this does not affect the avoided contribution to global warming, as they are in the same order of magnitude for both scenarios. In the case of avoided P and K, the benefits are mostly due to the avoided fossil CO_2.

The higher yield obtained in Scenario F (because overall, more N in a form available to the plants is applied, see section F.28 of Annex F) contributes to avoid the production of a given amount of crop, here modelled as wheat. This avoided wheat production also allow to avoid contributions to global warming (mostly through N_2O), though this is rather small, as illustrated on figure 4.2.A.

Overall, when the “deductions” from the avoided contributions to global warming are accounted for, managing the slurry as described in Scenario F (i.e. biogas production with fibre fraction from a mechanical-chemical separation and raw pig slurry) allows a net reduction of 103 kg CO_2 equivalent as compared to the reference scenario (figure 4.3).

Table 4.3 summarises, for selected processes, the contribution of the main contributing substances to global warming, for both Scenario A and F.

Table 4.3.
Scenario F vs A: Contribution of the main contributing substances to global warming for selected processes. **All values in kg CO_2 equivalent**. Soil JB3 (sandy).[1]

Processes		CH_4	Biogenic CO_2 (field)	N_2O	CO_2 (fossil or biogenic not from field processes)	Total emission (kg CO_2 equivalent) for the process
Scenario A (pig)						
In-house storage		75.67	0	11.16	3.44	90.3
Outdoor storage		44.62	0	16.00	0.18	60.8
Field processes		0	88.62	34.87	2.29[b]	125.9[a]
Scenario F						
In-house storage		75.67	0	11.16	3.44	90.3[a]
Outdoor storage	Liquid fraction	4.18	0	7.88	0.26	13.08[a]
	Degassed fibre fraction	0.52	0	0.47	0.70	1.76[a]
	Degassed liquid fraction	3.68	0	3.93	0.23	8.12[a]
Field processes	Liquid fraction	0	2.76	16.21	1.49[b]	20.53[a]
	Degassed fibre fraction	0	27.42	3.00	0.23[b]	30.66[a]
	Degassed liquid fraction	0	14.07	7.82	0.56[b]	22.46[a]
Biogas production		2.62	0	0.03	2.23[b]	5.34[a]
Co-generation heat and power		4.22	0	0.03	47.46	52.29[a]
Avoided electricity production		0	0	-0.53	-46.24[b]	-51.05[a]
Avoided heat production		0	0	-0.06	-16.15[b]	-17.25[a]

[1] The number of digits is *not* an expression of the uncertainty.
[a] The balance is from other global warming contributing substances not presented in this table.
[b] Fossil CO_2

Managing slurry as described in scenario F therefore appears as an interesting mitigation strategy as regarding the efforts to reduce the global warming impacts.

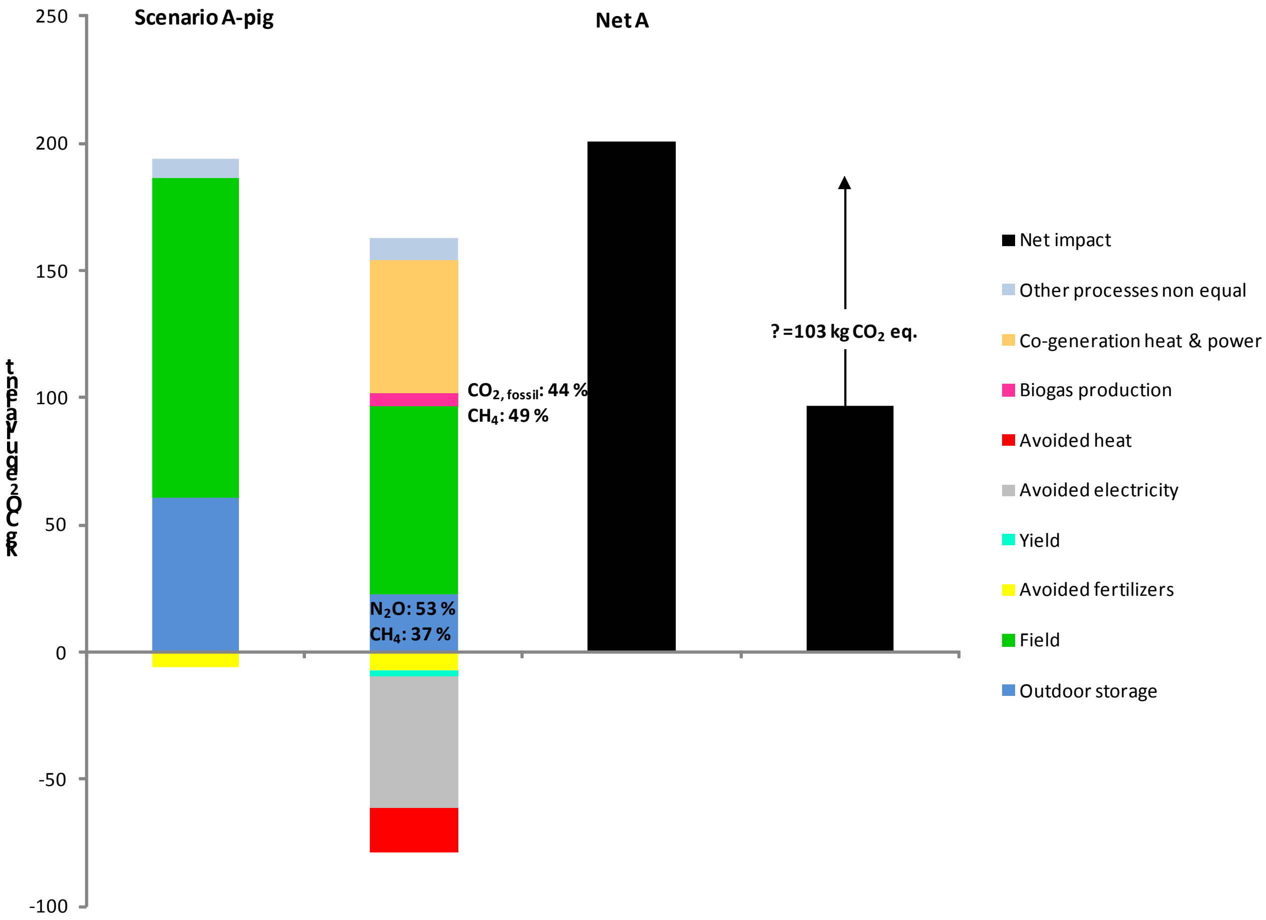
The major results as regarding global warming can be summarized as:

- Overall, managing the slurry as in Scenario F allows, based on the reference scenario considered, to reduce significantly the contributions to global warming from slurry management.
- There are 2 major hot spots regarding global warming:
    - In-house storage of slurry. The main contributor is CH_4.
    - Field processes. The main contributor is CO_2 due to the application of the different slurry fractions. The contribution to global warming from field process is much lower in the case of Scenario F as compared to Scenario A (however, in scenario F the biogenic CO_2 is emitted during the combustion of the biogas instead).
- Storing slurry in separated phases (with the separation efficiencies considered in Scenario F) has considerable benefits on global warming contribution as compared to storage of raw slurry.
- The contributions to global warming from the use of electricity, the use of polymer for separation and the transportation are rather negligible in both scenarios.
- Both scenarios allow avoiding the contributions to global warming from the production of inorganic N, P and K fertilisers in similar magnitude.
- Scenario F allows avoiding the production of marginal heat and electricity, which has considerable benefits on global warming

contributions. Avoided wheat production resulting from yield increases in Scenario F also contribute to additional avoided contributions to global warming, though the magnitude of it is rather small.

This information is summarised in figure 4.3. This figure presents the contribution to climate change of Scenario A and F only for the processes that are not equal between A and F (i.e. in-house storage and avoided N fertiliser are not included). All processes are presented; the category labelled “other processes non equal” represents the aggregation of all processes not presented in the legend.

Figure 4.3.
Comparison of Scenario F vs Scenario A for global warming including carbon sequestration, for processes differing between A and F only. Soil JB3, 10 years values.



4.2.3 Acidification

As it can be seen from figure 4.2.A, in-house storage and field processes are also the major two hot spots as regarding contribution to acidification:

- In-house storage, for both Scenario A and Scenario F, represent 60 % of the total positive contributions to acidification from the reference scenario.
- Field processes represent 31 % of the total positive contributions to acidification from the reference scenario in the case of Scenario A. For Scenario F, this represents 24 %.

As described in Annex F, there are no differences in the in-house storage between Scenario A and F. The main contributor to acidification for the in-house storage of slurry is NH_3, contributing to 99 % of the total acidification potential for this process. The other contributor to acidification from in-house slurry storage is NO_x, with the remaining 1 % of the total acidification potential for this process. This result is consistent with other LCA performed in the context of pig production (e.g. Dalgaard, 2007; Basset-Mens, 2005). Similarly, the estimate used to calculate NH_3 emissions from the housing system (i.e. 16% NH_3-N of the total-N “ex animal”) is similar to what has been used in other studies (e.g. Cederberg and Flysjö (2004) used a loss of 14 % of the excreted N).

In both scenarios, no mitigation technologies are considered in the pig housing system. Reduction of NH_3 from animal buildings has been widely investigated (one scenario involving reduction of NH_3 emissions potential from animal houses was investigated in the first part of this LCA foundation, see Wesnæs et al., 2009). Sommer et al. (2006), among others, provide an extensive overview of the different mitigation measures investigated in order to reduce NH_3 emissions from livestock buildings. Though the reduction of NH_3 from housing units is beyond the scope of this project, it nevertheless appears to be a hot spot that cannot be ignored in the whole slurry management system.

The degassed liquid fraction contribute to the biggest share of the acidification from field processes in Scenario F (55 %), followed by the separated liquid fraction (35 %) and the degassed fibre fraction (10 %). This is mainly due to NH_3 emissions. In fact, NH_3 is also the main contributor to acidification as regarding field processes from Scenario F (95 %; as compared to 4 % for NO_X and 1 % for SO_2). Emission of NH_3 during field application is in fact acknowledged as a major hot spot for NH_3 emissions in slurry management, together with emissions from livestock buildings.

The degassed liquid fraction presents higher emissions because NH_3 emissions from degassed slurry were estimated using the same estimates as for the raw slurry. This approach was used because, in one hand, anaerobic digestion contributes to increase the slurry pH and accordingly the proportion of total ammoniacal N (or TAN) in it. On the other hand, it has a lower DM content and is less viscous, which involves it has an increased infiltration rate and thereby the exchange possibility of NH_3 with the atmosphere is decreased (see section F.27.3, Annex F). Because of these contradictory effects, and because of the highly variable responses they have resulted in, in the available literature, it was decided to estimate the NH_3 emissions from the application of degassed slurry using the same estimations as for raw slurry. It is acknowledged that this may overestimate the acidification contribution from Scenario F. This emphasises the research needs related to this issue.

Apart from the in-housing slurry storage and the field processes, “co-generation of heat and power from the biogas” and “storage of degassed fibre fraction” can be distinguished as contributors to acidification for Scenario F, though their extent is much lower. For the “co-generation of heat and power”, the main contributor (91%) to acidification from the process is NO_X. This is emitted during the combustion of biogas in the biogas engine. The process “co-generation of heat and power” represents 5.8 % of the total positive contributions to acidification from the reference scenario.

For the “storage of degassed fibre fraction”, NH_3 is, as expected, the main contributor to the acidification potential. Emission of NH_3 from separated fibre fraction of animal slurries is recognised as a “hot spot” from slurry management involving separation (e.g. Amon et al., 2006; Petersen and Sørensen, 2008). In this study, it was considered that the degassed fibre fraction is stored in a covered storage platform. Due to the limited availability of data, it was considered that NH_3 emissions from the covered degassed fibre fraction are in the same order of magnitude as those from storage of pig farmyard manure. Lower NH_3 emissions were measured in one Danish study (Hansen et al., 2006) for the covered storage of degassed fibre fraction, but the authors themselves acknowledge their emissions for NH_3 are rather low. Moreover, the study of Hansen et al. (2006) involves no replication, so it is judged that more information to support these low values is needed in order to use them in the present LCA. The approach used in the present study for NH_3 emissions of the degassed fibre fraction is in fact based on a recommendation by the first author of the above-mentioned study (Hansen, 2009). Yet, though NH_3 from the degassed fibre fraction has the potential to be reduced as compared to what is considered in this study, it must be emphasised that the contribution to acidification from this process is only 4.3 % of the total positive contributions from the reference scenario. More significant gain may therefore be achieved by reducing the NH_3 emissions from in-house storage and field application.

The storage of the fibre fraction at the farm (process F.8), just before it is sent to the biogas plant, was assumed to be without any losses, due, among others, to the temporal nature of this process (see section F.8 of Annex F). Yet, as mentioned above, NH_3 from separated fibre fraction of animal slurries is recognised as a “hot spot” from slurry management involving separation, so this “no losses” assumption may have contributed to underestimate the overall acidification potential of Scenario F.

As for global warming, the contribution to acidification from the use of electricity, the use of polymer for separation, the transportation and the production of biogas (and not its combustion) are rather negligible.

Both scenarios allow avoiding the use of inorganic fertilisers and this contributes, in the two cases, to avoid the same magnitude of acidification potential. However, Scenario F also contributes to avoid the production of marginal heat and marginal electricity, which is translated by an additional contribution to avoid a share of acidification potential (see figure 4.2.A). For both avoided marginal heat and electricity, the main avoided contributor to acidification is SO_2. The higher yield in Scenario F contributes to avoid the production of a given amount of crop (here modelled as wheat) and consequently the related contribution to acidification from it. Yet, this is rather small, as it can be seen in table 4.1 and figure 4.2.A.

Overall, when the “deductions” from the avoided contributions to acidification are accounted for, managing the slurry as described in Scenario F (i.e. biogas production with fibre fraction from a mechanical-chemical separation and raw pig slurry) result in a difference of 3.4 m^2 area of unprotected ecosystem (UES) as compared to the reference scenario (figure 4.4). This difference is however compensated for when the uncertainties are taken into account (figure 4.10.A).

Table 4.4 summarises, for selected processes, the contribution of the main contributing substances to acidification, for both Scenario A and F.

Table 4.4.
Scenario F vs A: Contribution of the main contributing substances to acidification for selected processes. **All values in m^2 unprotected ecosystem (UES)**. Soil JB3 (sandy).[1]

Processes		NH_3	NO_X	SO_2	Total emission (m^2 UES) for the process
Scenario A (pig)					
In-house storage		29.77	0.37	0	30.14
Outdoor storage		3.09	0.93	0	4.02
Field processes		15.25	0.34	0.06	15.66[a]
Scenario F					
In-house storage		29.77	0.37	0	30.14
Outdoor storage	Liquid fraction	1.51	0.47	0.02	1.99[b]
	Degassed fibre fraction	2.16	0.01	0.00[c]	2.17[b]
	Degassed liquid fraction	1.23	0.23	0.01	1.47[b]
Field processes	Liquid fraction	4.06	0.19	0.04	4.29[b]
	Degassed fibre fraction	1.185	0.033	0.006	1.22[b]
	Degassed liquid fraction	6.47	0.28	0.02	6.77[b]
Biogas production		0.00[c]	0.02	0.05	0.08[a]
Co-generation heat and power		0.00[c]	2.64	0.26	2.90[b]
Avoided electricity production		-0.02	-0.44	-1.03	-1.67[a]
Avoided heat production		-0.01	-0.35	-1.57	-2.37[a]

[1] The number of digits is *not* an expression of the uncertainty.
[a] The balance is from other acidification contributing substances not presented in this table.
[b] This includes other contributing substances which are not reflected when contributions are presented with 2 decimal places.
[c] This is not a zero value.

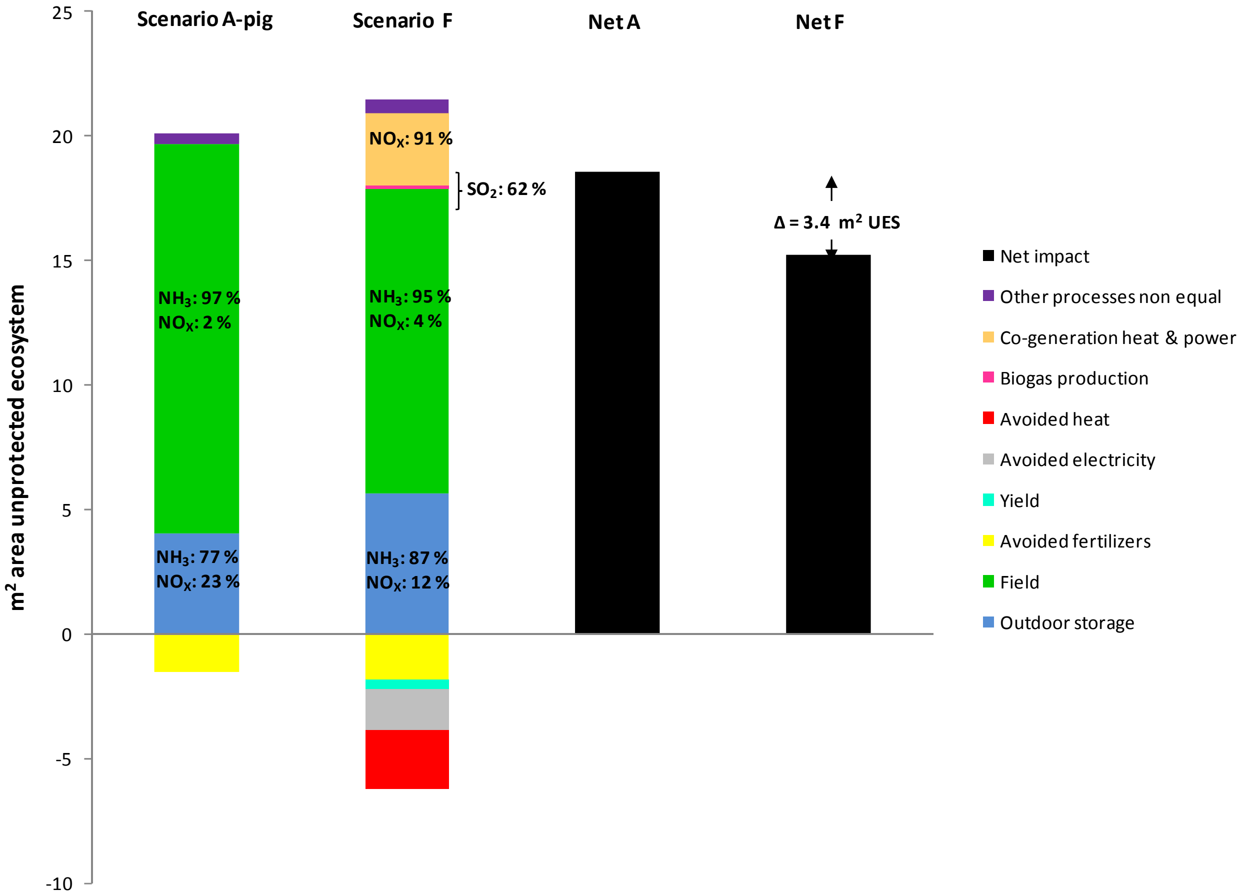
Based on these results, it can be concluded that managing slurry as described in Scenario F does not allow significant environmental benefits as regarding acidification potential, as compared to the reference slurry management.

The major results as regarding acidification can be summarised as:

- Overall, managing the slurry as in Scenario F does not allow significant environmental benefits as regarding acidification potential.
- There are 2 major hot spots are regarding acidification:
    - In-house storage of slurry. The main contributor is NH_3.
    - Field processes. The main contributor is NH_3.
- The overall contribution to acidification from outdoor slurry storage is greater for Scenario F and NH_3 is the main contributor. This is mostly due to the storage of the degassed fibre fraction.
- The contributions to acidification from the use of electricity, the use of polymer for separation, and the transportation are rather negligible in both scenarios.
- Both scenarios allow avoiding the contributions to acidification from the production of inorganic N, P and K fertilisers in similar magnitude. Scenario F also allows avoiding the production of marginal heat and electricity, which has additional benefits on acidification contributions. In a much smaller extent, the avoided wheat production resulting from increased yield also contributes to avoid contributions to acidification if Scenario F is implemented as compare to Scenario A.

This information is summarised in figure 4.4. This figure presents the contribution to acidification of Scenarios A and F only for the processes that are not equal between A and F (i.e. in-house storage and avoided N fertiliser are not included). All processes are presented; the category labelled "other processes non equal" represents the aggregation of all processes not presented in the legend.

Figure 4.4.
Comparison of Scenario F vs Scenario A for acidification, for processes differing between A and F only. Soil JB3, 10 years values.



4.2.4 Aquatic eutrophication (N)

There is, for this impact category, only one major hot spot: field processes. These represent, for Scenario A, 81 % of the total positive contributions to eutrophication (N) from the reference scenario (10 years value for C horizon in the field). For Scenario F, field processes represent 75 % of the total positive contributions to eutrophication (N) from the reference scenario (10 years value for C horizon in the field).

In Scenario F, the main contributors to N eutrophication from the field processes are N leached in soil (91 %) and re-deposited NH_3 (8 %). There are other contributing substances, but their contribution is so small, that it is not reflected when the proportions are expressed with no decimal place.

In the case of Scenario F, it is mainly the liquid and degassed liquid fractions that are concerned, as the contribution from the field processes related to the degassed fibre fraction are much lower. This, however, is simply due to the fact that a much smaller amount of degassed fibre fraction is applied to the field per functional unit (figure 4.1). Per functional unit, there is therefore much less N applied with the degassed fibre fraction (0.51 kg N per 1000 kg slurry ex-animal) than the liquid (2.56 kg N per 1000 kg slurry ex-animal) or the degassed liquid (2.11 kg N per 1000 kg slurry ex-animal) (table 4.2).

For both Scenarios A and F, all other processes (than field processes) are contributing rather insignificantly to aquatic N eutrophication. The exception is the in-house storage, which contribution represents, in both cases, 16.3 % of the total positive contributions to eutrophication (N) from the reference scenario (10 years value for C horizon in the field). The main contributor from this process is NH_3 (98 %), as in the case of acidification, which fosters the importance of mitigating NH_3 emissions from in-house slurry storage.

The production (and use) of inorganic N is avoided in both scenarios, and this contribute to a quite important avoidance of N-eutrophication to occur (61 % of the total positive contributions to N-eutrophication from the reference scenario, for both Scenario A and Scenario F). The avoided production of heat and electricity in Scenario F has a minor impact on the N-eutrophication potential avoided.

The avoided wheat production resulting from higher yield in Scenario F has here a more visible importance, the avoidance of N-eutrophication representing, considering the 10 years value for C horizon, 3.6% of the total positive contributions to N-eutrophication from the reference scenario (with the 100 years value for C horizon, it is 4.9 %).

Overall, when the “deductions” from the avoided contributions to N-eutrophication are accounted for, managing the slurry as described in Scenario F allows a net reduction of 0.11 kg N reaching aquatic recipients (characterisation unit for N-eutrophication potential) as compared to the reference scenario. This is for the 10 years value for C horizon in the field. When accounting for uncertainties, however, this benefit could be reduced to 0 (figure 4.10.A). Accordingly, there is no significant net reduction of N-eutrophication when comparing the biogas scenario F with the reference scenario A.

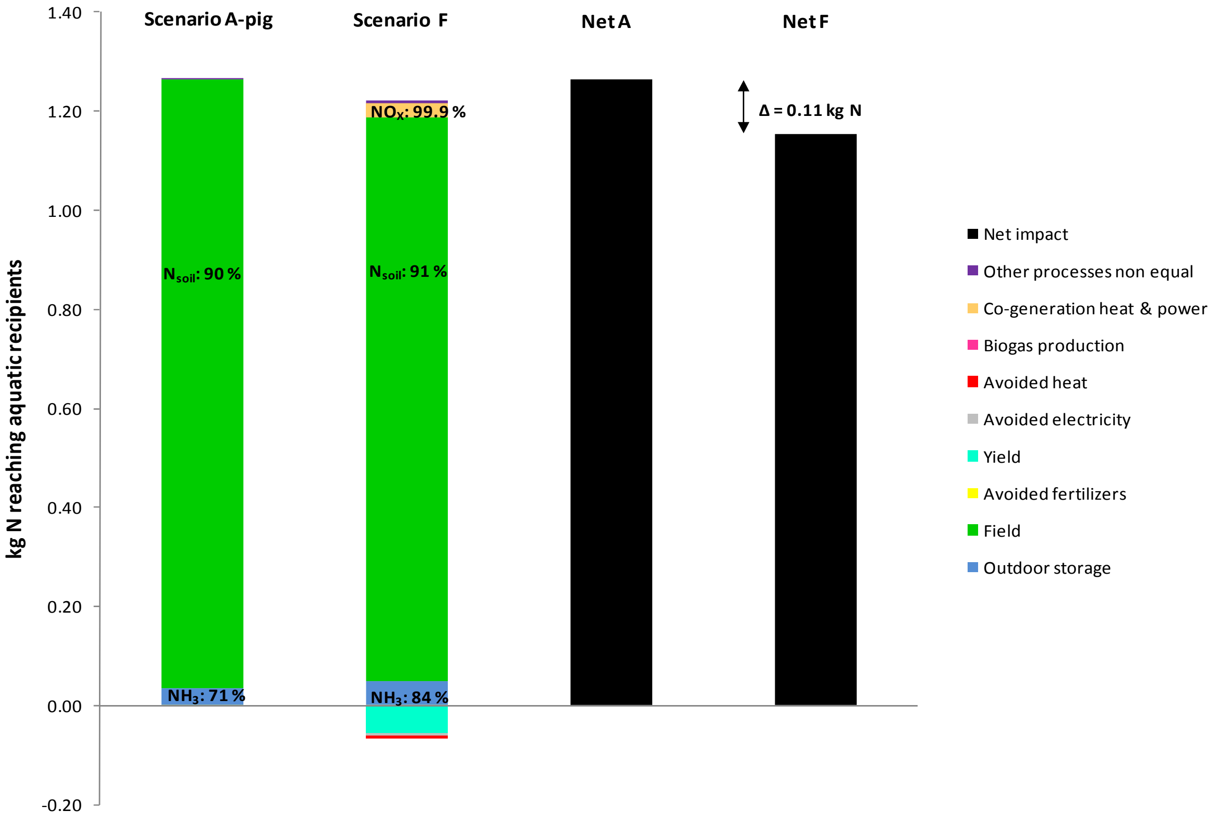
The major findings as regarding N-eutrophication potential can be summarised as:

- Managing slurry as described in Scenario F does allow a small benefit as regarding aquatic N-eutrophication, as compared to slurry management described in the reference scenario, however, when including uncertainties, the benefit is not significant, and might be negated.
- Field process is the main hot spot as regarding aquatic N-eutrophication: N leaching through soil is the main contributing substance to N-eutrophication for this process.
- In Scenario F, the overall contributions from field processes are slightly lower than in Scenario A, which highlights the positive effect of separation and digestion of slurry on aquatic N-eutrophication, though this is limited.
- In-house storage, in both scenarios, also has significant contributions to aquatic N-eutrophication, and this is mainly due to NH_3 emissions.

- Avoiding inorganic N fertilisers to be produced allows, in both scenarios, to avoid significant contribution to aquatic N-eutrophication.

This information is summarised in figure 4.5. This figure presents the contribution to N-eutrophication of Scenarios A and F only for the processes that are not equal between A and F (i.e. in-house storage and avoided N fertiliser are not included). All processes are presented; the category labelled "other processes non equal" represents the aggregation of all processes not presented in the legend.

Figure 4.5.
Comparison of Scenario F vs Scenario A for N-eutrophication, for processes differing between A and F only. Soil JB3, 10 years values.



4.2.5 Aquatic eutrophication (P)

For aquatic P-eutrophication, there is also one major hot spot: field processes, contributing to this environmental impact in approximately the same extent in both Scenario A and Scenario F. In both scenarios, it represents about 99 % of the total positive contributions to eutrophication (P) from the reference scenario, meaning that all other processes contribute rather insignificantly to this environmental impact.

For Scenario F, it can be highlighted that, for the field processes, the degassed fibre fraction contribute to about 60 % of the total positive contributions to eutrophication (P) from the reference scenario, while it is 31 % for degassed liquid fraction and 8.7 % for the liquid fraction. For field processes in Scenario F, P leaching to soil contributes to 99 % of the substances contributions to this impact category. For all organic fertilisers involved (liquid fraction, degassed fibre fraction and degassed liquid fraction), it was considered that P leaching to soil corresponds to 10 % of the P applied to field, and 6 % of this has the possibility to reach aquatic recipients (based on Hauschild and Potting, 2005). This is detailed in sections F.7, F.23 and F.27 of Annex F. The differences obtained between the two liquid fractions therefore reflect the efficiency of the first separation to separate the P in the solid fraction, thus explaining a much lower contribution from the liquid fraction.

The assumption used to estimate P leaching involves some uncertainties, as detailed in Wesnæs et al. (2009) (section 3.4.6 and section A.5.6, among others). In fact, the P actually reaching the aquatic recipients is also a function of the soil type and of the P already present in the soil. However, the purpose of the present study is comparative, and the same assumptions have been applied to both scenarios. In this perspective, the conclusions of this study are reliable, i.e. P leaching through soils is the main contributor to aquatic P-eutrophication for both scenarios. However, the “real” magnitude of P leaching through aquatic recipient (in kg P per 1000 kg slurry ex-animal) may be different than as presented in Annex A and F of the present study.

Avoiding inorganic P fertilisers to be produced and applied contribute, in both scenarios, to an important share of the avoidance of aquatic P eutrophication. This effect is however more important for Scenario F. This is because in Scenario F, the P is not applied in excess as most of it is applied via the degassed fibre fraction, which is applied on a field where P is the limiting nutrient for crop growth. Therefore, all organic P applied in Scenario F corresponds to avoided inorganic P, as compared to the reference scenario where only a share of the organic P substitute inorganic P, the rest being pure excess. To a much smaller extent, avoiding N and K fertilisers to be used and produced also allow to avoid P-eutrophication potential.

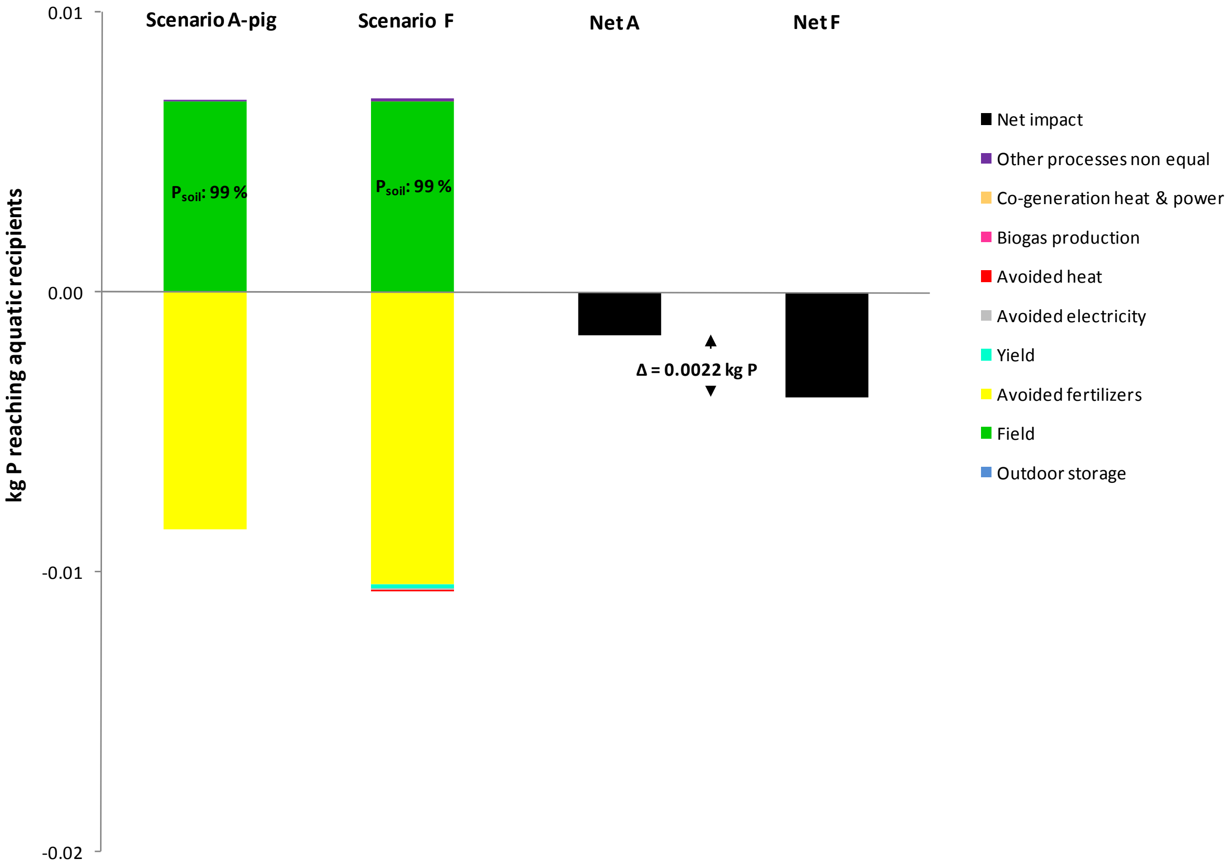
Similarly to N-eutrophication, the avoided wheat production resulting from higher yields in Scenario F has here some importance, the avoidance of P-eutrophication representing 2.4 % of the total positive contributions to P-eutrophication from the reference scenario.

Avoiding the production of marginal heat and electricity has, for Scenario F, only a minor effect on the avoidance of P-eutrophication potential.

One interesting point about P eutrophication potential is that it is an impact category where the net contributions are negative. This means that whether the slurry is managed as in Scenario A or F, the fact of avoiding inorganic P fertilisers to be produced/used overcome the contribution to P-eutrophication from managing the slurry itself. This statement, however, is only true if 1 kg P in slurry contributes equally to P-eutrophication as 1 kg P in mineral fertiliser, which might not be the case.

Overall, when the “deductions” from the avoided contributions toP-eutrophication are accounted for, there is a gain in managing the slurry as described in Scenario F as compared to the reference slurry management regarding contribution to P-eutrophication. The difference is 0.0022 kg P between Scenario A and F. This is illustrated in figure 4.6.

Figure 4.6.
Comparison of Scenario F vs Scenario A for P-eutrophication, for processes differing between A and F only. Soil JB3, 10 years values.



The major results as regarding P-eutrophication potential can be summarised as:

- Managing slurry as described in Scenario F results in a gain as compared to Scenario A.
- Field process is the main hot spot as regarding aquatic P-eutrophication: P leaching through soil is the main contributor to this process.

4.2.6 Photochemical Ozone Formation (“smog”)

In both scenarios, there are 2 main hot spots for photochemical ozone formation. Common to both scenarios is:

- In-house storage, representing about 56 % of the total positive contributions to photochemical ozone from the reference scenario.

For Scenario A, outdoor storage is also a hot spot for ozone formation, representing 39 % of the positive contributions from the reference scenario. For Scenario F, the co-generation of heat and power is the second hot-spot, representing 24 % of the positive contributions from the reference scenario.

In the case of in-house storage, the main contributor is CH_4, which represents about 95 % of the contribution to ozone formation for this process. The overall emissions of CH_4 from in-house may have been overestimated, as discussed in section 4.2.2. The alternative MCF value for estimating CH_4

from in-house slurry storage (see description section 4.2.2) would lead to a reduction of 0.07859 person*ppm*h, representing a reduction of about 78 % of the ozone formation potential. In spite of this, CH_4 would remain the main contributor to ozone formation for in-house storage.

For co-generation of heat and power, the main contributor is NO_x, representing about 85 % of the contribution to ozone formation for this process. This is emitted during the combustion of biogas in the biogas engine.

In Scenario A, CH_4 emission is the main contributing substance (95 %) to ozone formation impact for the outdoor storage process. As it can be observed in table 4.1, slurry storage is much less significant for Scenario F than Scenario A. This is due, as described in section 4.2.2, to the lower VS content of separated and degassed slurry, thus involving a much lower potential for CH_4 emissions. This again highlights the positive effect of slurry separation and digestion as regarding CH_4 emissions during slurry storage.

Avoiding inorganic fertilisers to be produced (N, but to a smaller extent P and K) also contribute to reduce the contribution to ozone formation, in similar magnitude for both scenarios. However, the avoided production of marginal heat and electricity in Scenario F contribute to “extra” avoidance of contribution to photochemical ozone. So does the avoided wheat production induced by increased yield, but this represent a rather small avoided contribution.

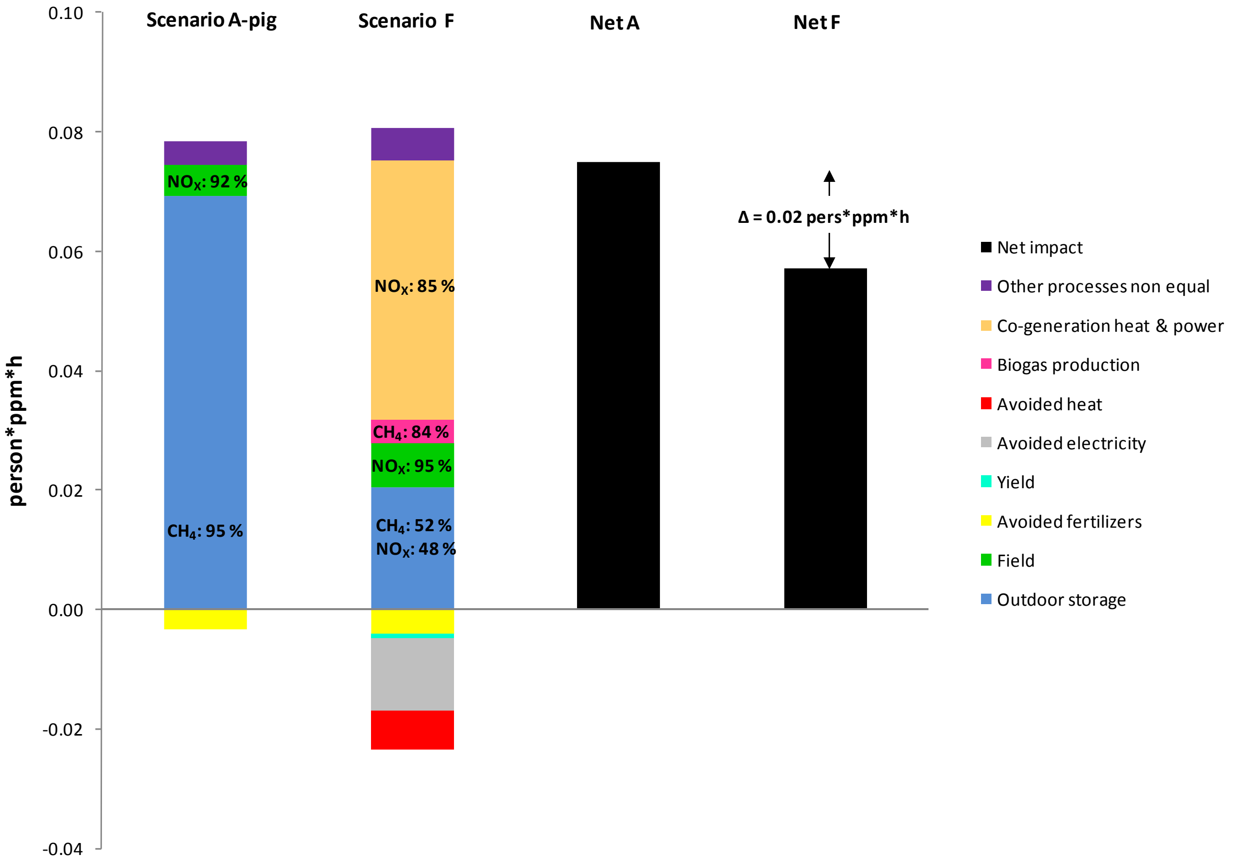
Overall, when the “deductions” from the avoided contributions to photochemical ozone formation are accounted for, the difference between managing the slurry as described in Scenario F as compared to the reference scenario is 0.02 pers*ppm*h. However, when taking the uncertainties into account, this difference is not significant (figure 4.10.A).

The major results as regarding photochemical ozone formation potential can be summarised as:

- There are no significant benefits in managing the slurry as in Scenario F for the impact category photochemical ozone formation.
- For both scenarios, in-house storage is a hot spot process as regarding ozone formation impact, essentially because of CH_4 emissions.
- For Scenario F, the emissions of NO_x during the combustion of biogas for co-generation of heat and power also contribute significantly to ozone formation potential.
- Contributions to ozone formation during slurry storage are much lower in Scenario F as compared to Scenario A due to the positive effect of slurry separation and digestion on CH_4 emission potential.

This information is summarised in figure 4.7. This figure presents the contribution to photochemical ozone formation of Scenarios A and F only for the processes that are not equal between A and F (i.e. in-house storage and avoided N fertiliser are not included). All processes are presented; the category labelled “other processes non equal” represents the aggregation of all processes not presented in the legend.

Figure 4.7.
Comparison of Scenario F vs Scenario A for photochemical ozone formation, for processes differing between A and F only. Soil JB3, 10 years values.



4.2.7 Respiratory inorganics (small particles)

This impact category involves, for both scenarios, 2 main contributing processes. These are:

- In-house storage of slurry, representing, for both scenarios, about 56 % of the total positive contributions to respiratory inorganics from the reference scenario.
- Field processes
    - Scenario A: This represents about 31 % of the total positive contributions to respiratory inorganics from the reference scenario.
    - Scenario F: This represents about 25 % of the total positive contributions to respiratory inorganics from the reference scenario (9% liquid fraction; 2% degassed fibre fraction and 14 % degassed liquid fraction).

For Scenario F, another important contributor is the co-generation of heat and power from biogas, representing 14 % of the total positive contributions to respiratory inorganics from the reference scenario.

For in-house storage, the main contributor is NH_3 emissions, representing about 97 % of the contribution to respiratory inorganics for this process. This, as discussed in section 4.2.3, emphasises the importance of reducing NH_3 from animal buildings.

For field processes, in Scenario F, NH_3 is also the main contributor to respiratory inorganics, accounting for 86 % of the contributions for this process. The contribution from the degassed liquid fraction is higher than the other two organic fertilisers for the same reasons as explained in section 4.2.3 (acidification).

Co-generation of heat and power from the biogas has for main contributor to “respiratory inorganics” NO_x, which are emitted during the combustion of the biogas in the biogas engine (NO_x represents 96 % of the total contributions to respiratory inorganics for this process).

Avoiding inorganic fertilisers to be produced (N, but to a smaller extent P and K) also contribute to reduce the contribution to respiratory organics, in similar magnitude for both scenarios. However, the avoided production of marginal heat and electricity in Scenario F contribute to “extra” avoidance of contribution to respiratory inorganics. So does the avoided wheat production induced by increased yield, but this represents a rather small avoided contribution.

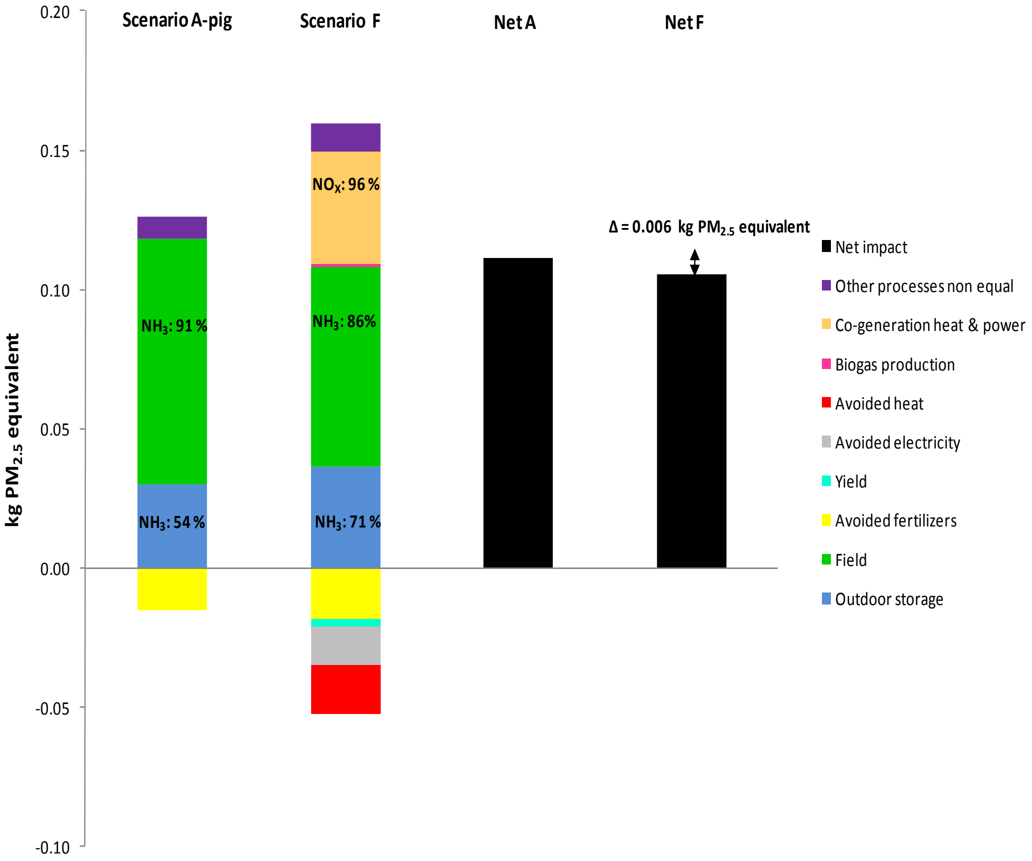
Overall, when the “deductions” from the avoided contributions to respiratory inorganics are accounted for, the difference between managing the slurry as described in Scenario F as compared to the reference slurry management amount to 0.006 kg $PM_{2.5}$ equivalent. When accounting for uncertainties, this difference is however not significant (figure 4.10.A).

The major results as regarding respiratory inorganics potential can be summarised as:

- No significant benefits are obtained with Scenario F as compared to the reference scenario for the impact category “respiratory inorganics”.
- Two main processes contribute to respiratory inorganics : in-house storage of slurry and field processes, for both Scenario F and the reference scenario. For these two processes, the main responsible substance to “respiratory inorganics” is NH_3.
- Co-generation of heat and power for Scenario F also contributes significantly to “respiratory inorganics”, and in this case it is mainly due to NO_x emissions during biogas combustion in the engine.

This information is summarised in figure 4.8. This figure presents the contribution to “respiratory inorganics” of Scenarios A and F only for the processes that are not equal between A and F (i.e. in-house storage and avoided N fertiliser are not included). All processes are presented; the category labelled “other processes non equal” represents the aggregation of all processes not presented in the legend.

Figure 4.8.
Comparison of Scenario F vs Scenario A for “respiratory inorganics”, for processes differing between A and F only. Soil JB3, 10 years values.



4.2.8 Non-renewable energy resources

This category involves 2 main hot spots:

- Transport processes, for both Scenario A and F;
- Use of energy (mostly electricity but also heat). This is translated by:
  - Process “outdoor storage-elect” for Scenario A
  - Process “Biogas production” for Scenario F

For transport in Scenario F, the main contributor is crude oil, representing 65 % of the contributions from the transport process. This is mainly due to the diesel used to fuel the tractors and to transport the slurry by trucks between the farm and the biogas plant. This category is the only category where transport is significant. In Scenario A, transport processes contributed to 36.8 % of the total positive contributions to “use of non-renewable energy resources” from the reference scenario while in Scenario F, it is 51 %. This is because overall, much more transport is involved in Scenario F, as the slurry has to be transported to the biogas plant and come back.

The process requiring energy inputs appeared as hot spots for the non-renewable energy resources. For Scenario F, the production of biogas can be highlighted, representing 51 % of the total positive contributions to “use of non-renewable energy resources” from the reference scenario. The main contributors to the “non-renewable energy resources” impact from this process are hard coal (52 %) and natural gas (43 %). This is because of the consumption of electricity for running the anaerobic digestion process (see section F.15.3, Annex F). The electricity consumption for producing biogas was estimated as 5% of the net energy production from the biogas. As discussed in section F.15.3 of Annex F, this may however be higher and represent 10 % of the net energy production. In such a case, this would simply double to amount of energy used, and increase the contribution of the biogas production process to the "non-renewable energy resources" category accordingly. The heat consumption for the process was calculated based on heating the biomass mixture from 8°C to the process temperature of 37°C (a temperature difference of 29°C). Reducing this temperature difference through heat exchangers would contribute to slightly attenuate the contribution from the biogas process to the present impact category, but this is likely to represent a rather small contribution overall, as the negative contributions for this impact category are much larger than the positive contributions.

This means, in the case of Scenario F, that producing biogas allow avoiding the consumption of non-renewable energy much more than it contributes to it. This is particularly due to the consumption and production of marginal electricity that is avoided, but also to avoided marginal heat and fertilisers (particularly N). Avoiding fertilisers to be produced and used also has a positive effect on the non-renewable energy consumption for Scenario A, and such benefits are in the same order of magnitude for both scenarios, except for P where a little more non-renewable energy is saved in the case of Scenario F.

In the case of Scenario F, the avoided wheat production induced by higher yield also contributes to avoided contributions to "non-renewable energy" impact category, but this is rather small as compared to the contributions from the avoided fertilisers and avoided energy.

For this impact category, all storage process appears rather insignificant contributors, as they all require little or no energy input.

Overall, when the "deductions" from the avoided contributions to non-renewable energy use are accounted for, managing the slurry as described in Scenario F allows a reduction of 834 MJ of (primary) non-renewable energy use as compared to the reference scenario.

The major results as regarding the use of non-renewable energy resources can be summarised as:

- Managing the slurry as described in Scenario F allows very important reductions of the use of non-renewable energy resources, as compared to the management of slurry as in the reference scenario.
- For Scenario F, the positive contributions to this impact are about the double of those from Scenario A; on the other hand, the avoided contributions to this impact are more than 3 times higher for Scenario F than Scenario A, which makes Scenario F overall more environmentally beneficial as regarding this impact category.
- The main contributors to this impact are transport processes as well as processes involving energy input. In both cases, the main contributors are fossil resources use (crude oil, hard coal and natural gas, among others).
- Avoiding marginal electricity to be produced (through the use of biogas for electricity) contribute significantly to avoid the consumption of non-renewable resources. To an important (but

smaller) extent, avoiding N fertilisers to be produced as well as marginal heat also contribute to avoid an important magnitude of "non-renewable energy resources consumption".

4.2.9 Consumption of phosphorus as a resource

This impact category aims to reflect the importance of phosphorus as a limited and valuable resource. Accordingly, any scenario allowing preventing the use of this limited resource can be highlighted. In the case of this study, this category allows to emphasise the benefits of using slurry as an organic source of P rather than using inorganic P from the limited reserves. As Scenario F allows to save more P (because all the slurry P contributes to avoid inorganic P to be produced, the P not being applied in excess as in Scenario A: section A.6.1 of Annex A and F.28.4 of Annex F), it provides more benefits as compared to Scenario A regarding this impact category. The avoided wheat production induced by higher yields in Scenario F also allows a tiny additional contribution in avoiding P resources to be consumed.

Based on this result, it can be concluded that managing slurry as described in Scenario F offers more advantages over Scenario A as regarding the consumption of P (the difference is 0.33 kg P being saved, per functional unit). This is due to a better management of the P in Scenario F, as the P is concentrated in the solid fraction which is applied in a field where P is deficient. Yet, if this P would be applied in excess as in Scenario A, this benefit would be lost, which highlights the importance of using the P-rich fertiliser produced in Scenario F in a field where it is needed.

4.2.10 Carbon stored in soil

Through Scenario F, a certain amount of C ends up to be stored in soils, which means that this C is not going to the atmospheric C pool. This is through the C of the different slurry fractions that are applied to field and not emitted as CO_2.

For the reference scenario, a total of 3.61 kg C per 1000 kg pig slurry ex-animal is stored in soils, corresponding to 13.2 kg CO_2 not emitted per functional unit. This is for a C horizon in the field of 10 years. With the 100 years values, more CO_2 is emitted and consequently less C is stored per functional unit (1.03 kg), resulting to 3.8 kg CO_2 not emitted per 1000 kg pig slurry ex-animal. These values are presented in table 4.1 of Wesnæs et al. (2009).

For Scenario F, less C is added to field per functional unit but also less CO_2 is emitted in the field (as this CO_2 has been emitted already during the combustion of biogas). As a result, the amount of C sequestrated in the soil per functional unit (3.36 kg C considering 10 years values; 0.94 kg C considering 100 years values) is similar to the amount of C sequestrated for the reference scenario. In terms of CO_2 avoided, this corresponds to 12.3 kg CO_2 (10 years values) and 3.4 kg CO_2 (100 years values) per 1000 kg pig slurry ex-animal.

4.2.11 Polymer

This scenario involves the use of cationic polyacrylamide (PAM) as a polymer during the separation (0.90 kg cationic PAM per 1000 kg slurry input in the separation process). This represents 0.76 kg PAM per functional unit. The impact of the polymer fabrication was considered in the assessment, but the fate of this polymer in the environment could not be assessed due to a lack of data.

Polyacrylamide polymer can be defined as many units of the monomer acrylamide, which toxicity is acknowledged as a major concern, this component being known to affect the central and peripheral nervous system (ICON, 2001). Once the PAM degrades to acrylamide monomer, the monomer is then subjected to rapid degradation in which it is decomposed to ammonia and to acrylic acid ($CH_2CHCOOH$), which in turn is degraded to CO_2 and water (ICON, 2001). Because of the extremely rapid degradation of the acrylamide monomer, it is reported that it is unlikely to find this toxic product in the environment as a result of PAM degradation (Sojka et al., 2007).

Based on the literature available, it is assumed that the PAM is not likely to be degraded during the anaerobic digestion. This is based, among others, on results from studies where the solid fraction from PAM-separated slurry was digested for biogas production. This is further described in Annex F, section F.4.3.

Based on this, it was assumed that all the PAM end up in the degassed fraction (liquid and degassed). As regarding the fate of cationic PAM, many of the studies reviewed suggested that PAM is rather recalcitrant to biological degradation. This is explained, among others, by the high molecular weight of PAM that cannot pass through the biological membranes of the bacterium. However, PAM is more susceptible to undergo thermal degradation (temperatures above 200 °C), photodegradation, chemical degradation (under very acidic or very basic conditions) as well as mechanical degradation (if submitted to high shear). Yet, none of the required conditions for these are likely to be found in an agricultural field, as detailed in section F.23.10. This led to the assumption that the PAM accumulates in the environment, in the soil and water compartments (linear PAM is soluble in water).

As regarding the effect of cationic PAM on living organisms, Sojka et al. (2007) report that the LC_{50} values (i.e. the amount causing the death of 50 % of a group of tested animals) of cationic PAM is in the range of 0.3 to 10 ppm. These authors also report that cationic PAM bind to sites rich in haemoglobin such as fish gills, thus posing a barrier to oxygen diffusion.

Acknowledging this information, it is recognised that the use of this 0.76 kg of cationic PAM per 1000 kg slurry ex-animal may represents an important concern in the environment that could not be reflected in this life cycle assessment. Given the importance of the potential risk associated with the cationic PAM fate in the environment, it is suggested to investigate this aspect more deeply before implementing any large scale slurry management projects involving the use of cationic PAM.

4.3 Uncertainties

The uncertainties on the compared results have been estimated by analysing the most important factors that are ***changed***, when comparing scenario F with the reference scenario A. It means that the uncertainties for each scenario is not analysed as such, but only the emissions that are important for the

differences. The uncertainties on the comparisons are based on estimates of the uncertainties on those emissions that are the most important for the changes.

The uncertainties are related to the total positive contributions from the reference scenario A (i.e. the total that is set to 100% in figures 4.9 and 4.10 as “index”).

The values of the uncertainty ranges are shown in table 4.5.

4.4 Synthesis of the results for all impact categories assessed

Table 4.5 compares the overall characterised results of Scenario A versus Scenario F, for all impacts categories (including carbon stored in soils). It also presents the uncertainty ranges for all impact category results.

Figures 4.9.A and 4.9.B illustrate the results presented in table 4.5, and give an impression of the uncertainty. The difference between these two figures is the axis, which has a greater range in the case of figure 4.9.B in order to capture the whole impacts of non-renewable energy consumption. Figures 4.10.A and 4.10.B present only the net differences between Scenario A and F, including the uncertainties.

Table 4.5.
Comparison of the impacts from Scenario A (reference) versus Scenario F (biogas from raw pig slurry + fibre fraction from chemical-mechanical separation). The number of digits is *not* an expression of the uncertainty.

Impact category	Scenario A - pig	Scenario F	Difference, i.e. Biogas scenario F minus Reference scenario A	Conclusion
Global warming (during 10 years) [kg CO_2 eq.]				
Positive contributions:	+284 kg	+ 253 kg	-103 [-154 to -80] kg CO_2 eq.	28-54% reduction of positive contributions from scenario A
Negative contributions:	- 36 kg	- 109 kg		
Net:	= 248 kg	= 144 kg		
Global warming (during 100 years) [kg CO_2 eq.]				
Positive contributions:	+ 304 kg	+ 274 kg	-104 [-154 to -80] kg CO_2 eq.	26-51% reduction of positive contributions from scenario A
Negative contributions:	- 47 kg	- 120 kg		
Net:	= 257 kg	= 154 kg		
Acidification [m^2 UES, i.e. area of unprotected ecosystem]				
Positive contributions:	+ 50.3 m^2	+ 51.6 m^2	-3.4 [-14 to +3] m^2 UES	No significant difference due to uncertainties
Negative contributions:	-5.5 m^2	-10.2 m^2		
Net:	= 44.8 m^2	= 41.4 m^2		
N-eutrophication (aquatic) (during 10 years) [kg N - amount reaching aquatic recipients]				
Positive contributions:	+ 1.51 kg	+ 1.47 kg	-0.11 [-0.23 to +0.11] kg N	No significant difference due to uncertainties
Negative contributions:	- 0.93 kg	- 0.99 kg		
Net:	= 0.59 kg	= 0.48 kg		
N-eutrophication (aquatic) (during 100 years) [kg N - amount reaching aquatic recipients]				
Positive contributions:	+ 1.63 kg	+ 1.64 kg	-0.08 [-0.16 to +0.01] kg N	No significant difference due to uncertainties
Negative contributions:	- 1.03 kg	- 1.11 kg		
Net:	= 0.61 kg	= 0.53 kg		
P-eutrophication (aquatic) [kg P - amount reaching aquatic recipients]				
Positive contributions:	+ 0.0069 kg	+ 0.0069 kg	-0.0022 [-0.0044 to -0.0011] kg P	16-64% reduction of positive contributions from scenario A
Negative contributions:	- 0.0086 kg	- 0.0108 kg		
Net:	= -0.0017 kg	= -0.0039		
Photochemical ozone formation [person.ppm.hr - see section 3.4.7]				
Positive contributions:	+ 0.179 p.p.h	+ 0.18 p.p.h	-0.018 [-0.068 to +0.032] p.p.h	No significant difference due to uncertainties
Negative contributions:	- 0.014 p.p.h	-0.03 p.p.h		
Net:	= 0.17 p.p.h	= 0.15 p.p.h		
Respiratory Inorganics [kg PM2.5 eq, i.e. kg equivalents of 2.5 µm size particles]				
Positive contributions:	+ 0.29 kg	+ 0.32 kg	-0.0041 [-0.043 to +0.046] kg PM2.5	No significant difference due to uncertainties
Negative contributions:	- 0.05 kg	- 0.09 kg		
Net:	= 0.24 kg	= 0.23 kg		
Non-renewable energy [MJ primary energy]				
Positive contributions:	+ 151 MJ	+ 237 MJ	-834 [-1084 to -584] MJ	380-710% reduction of positive contributions from scenario A
Negative contributions:	-369 MJ	-1288 MJ		
Net:	= -217 MJ	= -1051 MJ		
Phosphorus Resources [kg P]				
Positive contributions:	0 kg	0 kg	-0.33 [-0.66 to -0.15) kg P	A significantly larger amount of P resources saved in scenario F
Negative contributions:	- 1.34 kg	- 1.67 kg		
Net:	= -1.34 kg	= -1.67 kg		
Carbon stored in soil during 10 years [kg C] **and corresponding amount of CO_2-eq**				
C added with slurry:	+ 31.7 kg C	+ 19.5 kg C	-0.25 [-1.3 to +0.8] kg C -0.9 [-4.9 to +3.0] kg CO2	No significant difference due to uncertainties
C lost as CO2:	-28.1 kg C	-16.1 kg C		
C stored in soil:	= 3.6 kg C	= 3.4 kg C		
Net CO2:	= 13.2 kg CO_2	= 12.3 kg CO_2		
Carbon stored in soil during 100 years [kg C] **and corresponding amount of CO_2-eq**				
C added with slurry:	+ 31.7 kg C	+ 19.5 kg C	-0.1 [-0.4 to +0.2] kg C -0.3 [-1.6 to +0.8] kg CO_2	No significant difference due to uncertainties
C lost as CO2:	-30.7 kg C	-18.5 kg C		
C stored in soil:	= 1.0 kg C	= 0.94 kg C		
Net CO2:	= 3.8 kg CO_2	= 3.4 kg CO_2		

Note: All numbers are all rounded and accordingly, if the reader calculates the difference, it might vary slightly from the numbers shown in the table.

Figure 4.9.A
Comparison of the environmental impacts from Scenario A (reference) versus Scenario F (biogas from raw pig slurry + fibre fraction from mechanical-chemical separation). Axis ranging from -180 to 120.

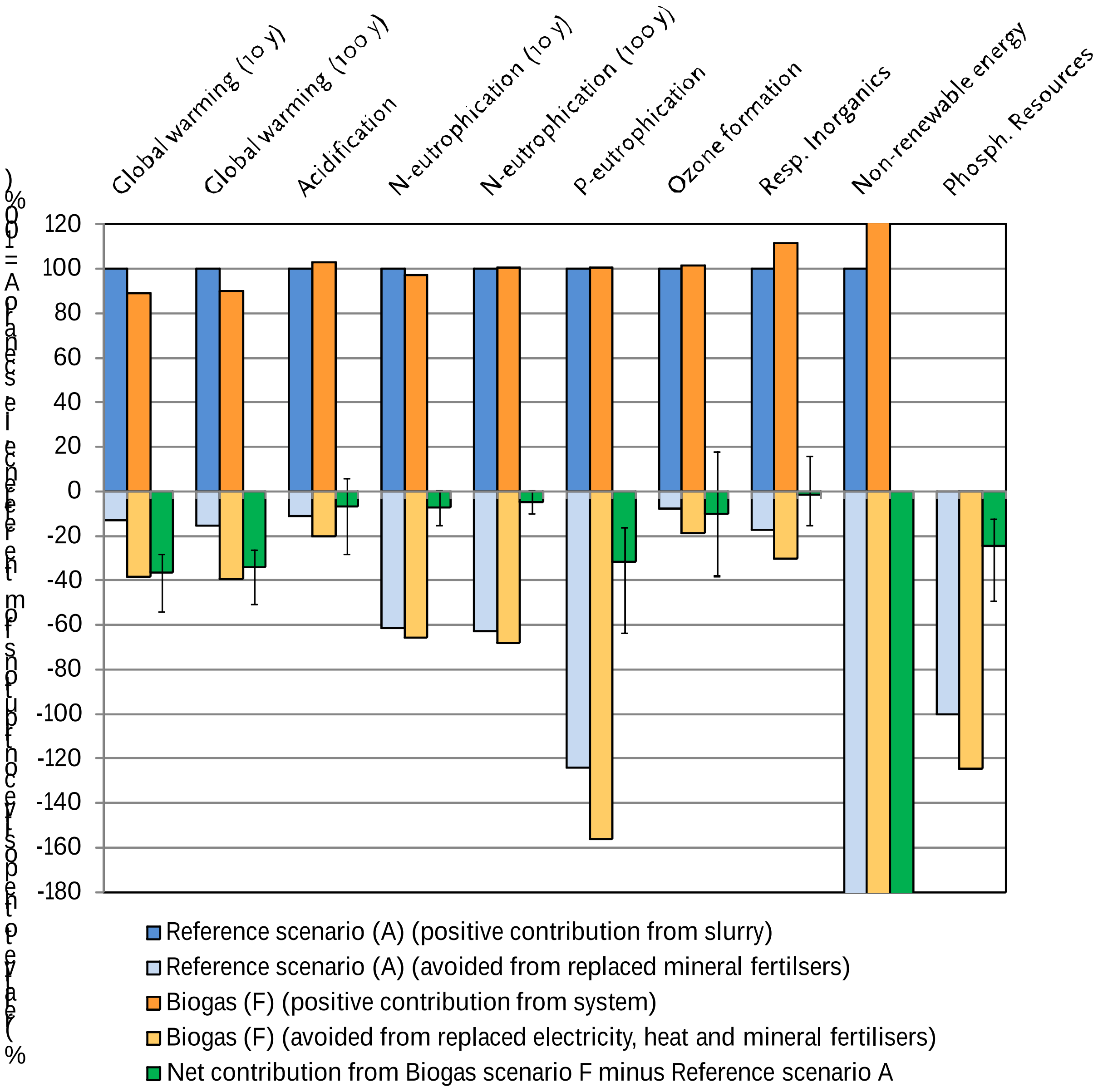


Figure 4.9.B
Comparison of the environmental impacts from Scenario A (reference) versus Scenario F (biogas from raw pig slurry + fibre fraction from mechanical-chemical separation). Axis ranging from -1000 to 200.

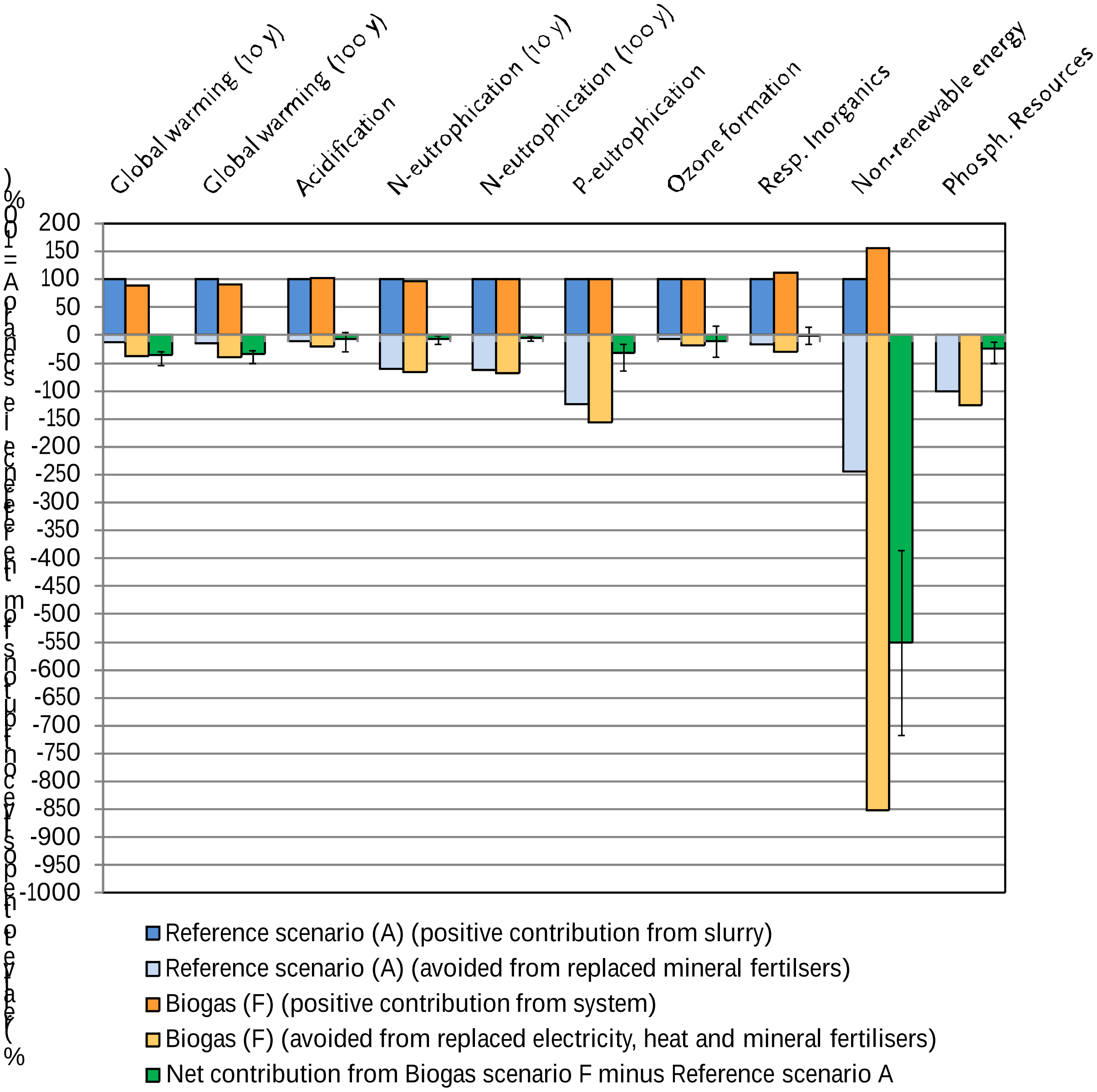


Figure 4.10.A
Comparison of the environmental impacts from Scenario A (reference) versus Scenario F (biogas from raw pig slurry + fibre fraction from mechanical-chemical separation). Net difference only. Axis ranging from -100 to 100.

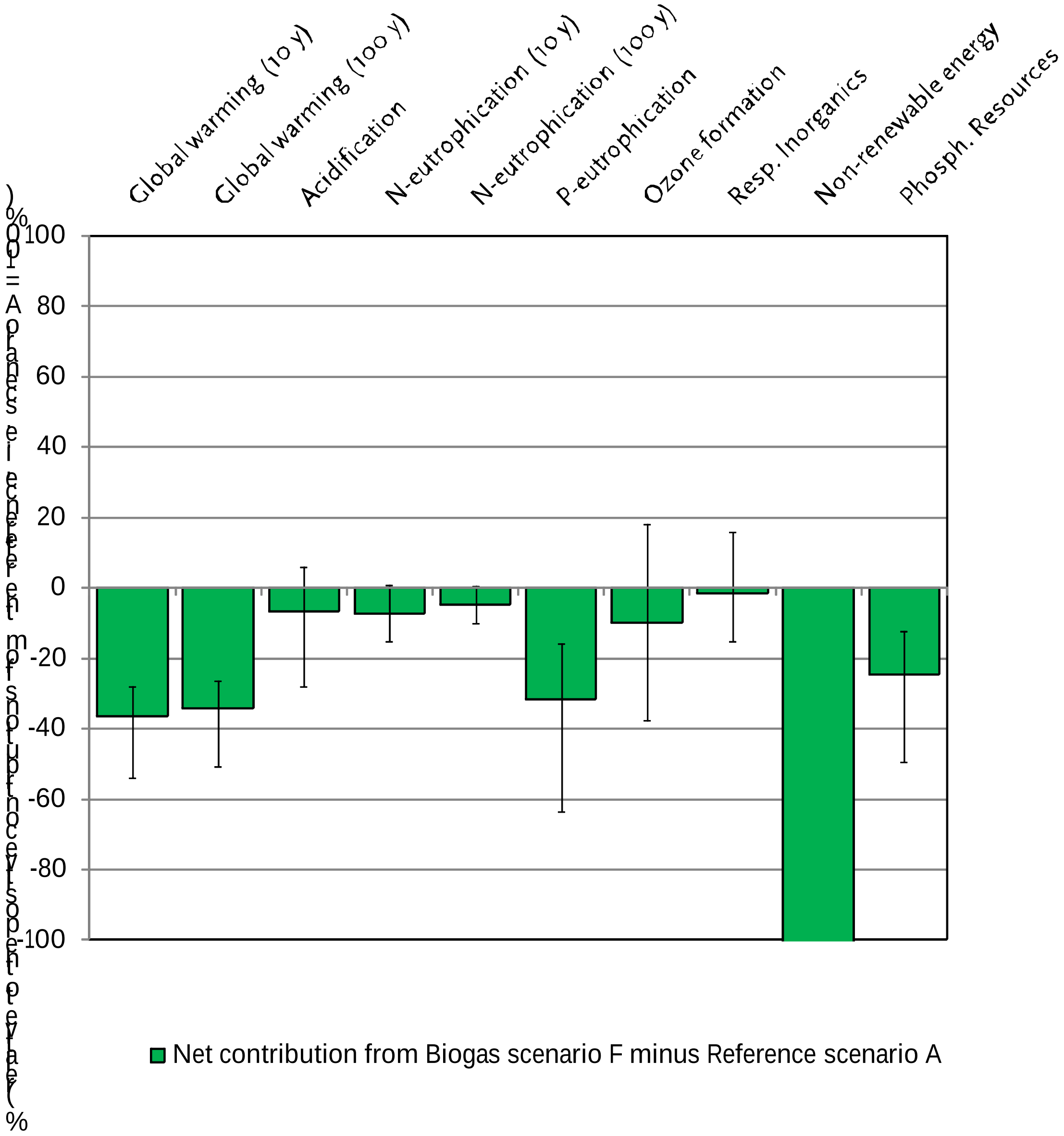
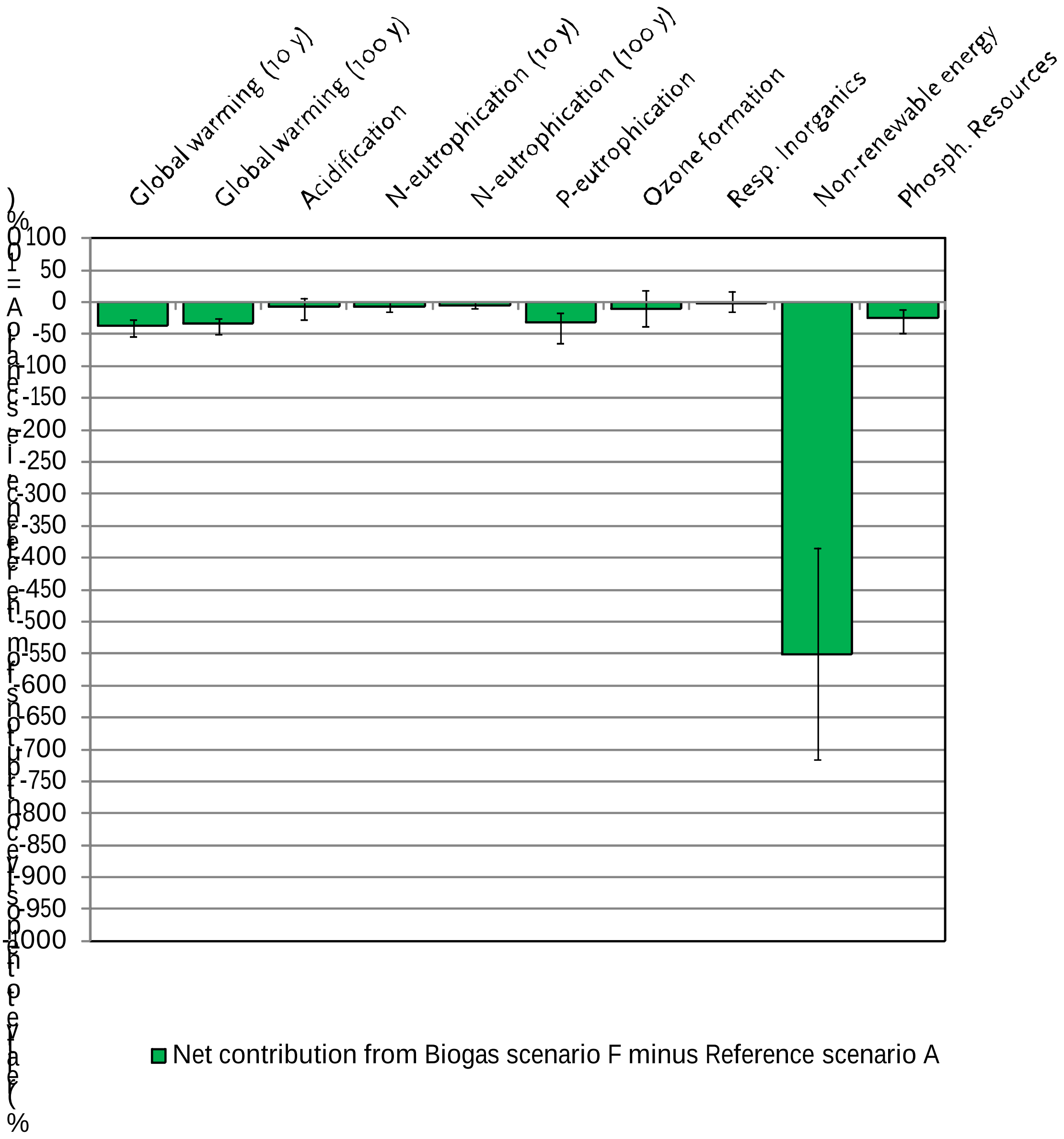


Figure 4.10.B
Comparison of the environmental impacts from Scenario A (reference) versus Scenario F (biogas from raw pig slurry + fibre fraction from mechanical-chemical separation). Net difference only. Axis ranging from -1000 to 100.



5 Biogas production from raw cow slurry and fibre fraction from mechanical-chemical separation (Scenario G) – results and interpretation

This section presents the results and the interpretation from the life cycle assessment carried out for "Scenario G", described below. The results from "Scenario G" are compared to those of the reference scenario for dairy cow slurry management, i.e. "Scenario A". Doing so, it is therefore possible to answer the research question: "***What are the environmental benefits and disadvantages of producing biogas from raw cow slurry and the fibre fraction obtained from a mechanical-chemical separation process, as compared to the reference situation for cow slurry management?"***

As it was done for Scenario F, Scenario G was built in such a way that it integrates the "best available technologies" as well as the "best possible practices" as much as possible for an optimal environmental performance. This is important to remember in the results interpretation.

The detailed description of this scenario, including all mass balances, assumptions and calculations, is presented in Annex G. All life cycle inventory data used for the results presented in this section can therefore be found in Annex G.

5.1 System Description

The system constituting Scenario G, as described in section 2.2.3, consists to produce biogas from a mixture of fibre fraction (from mechanically separated slurry, flocculated with polymer) and raw slurry, both from dairy cows. After excretion, raw slurry is stored in-house; part of it is separated and part of it is kept as raw slurry. These fractions do not necessarily come from the same farm (and most probably they do not), but they both end up at the biogas plant. Once at the biogas plant, these fractions are mixed according to their composition and to their degradability in order to achieve realistic production conditions. The separation process used is considered as a "best available technology" as regarding its efficiency to increase the relative fraction of dry matter and nutrients transferred to the fibre fraction. While the separated liquid fraction is stored and used on-field as an organic fertiliser, the separated fibre fraction, as well as the raw slurry, is then used as an input for biogas production. The temporal storage of the fibre fraction before the fibre is used for biogas production is assumed to be rather short (range of 1 to 3 days with 7 days as a maximum), which is considered as a "best management practice". Similarly, it was assumed that the raw slurry is stored in the pre-tank for a duration of less than 14 days before it is transferred whether to the biogas plant or to the separation process, which is also considered as a “best management practice”.

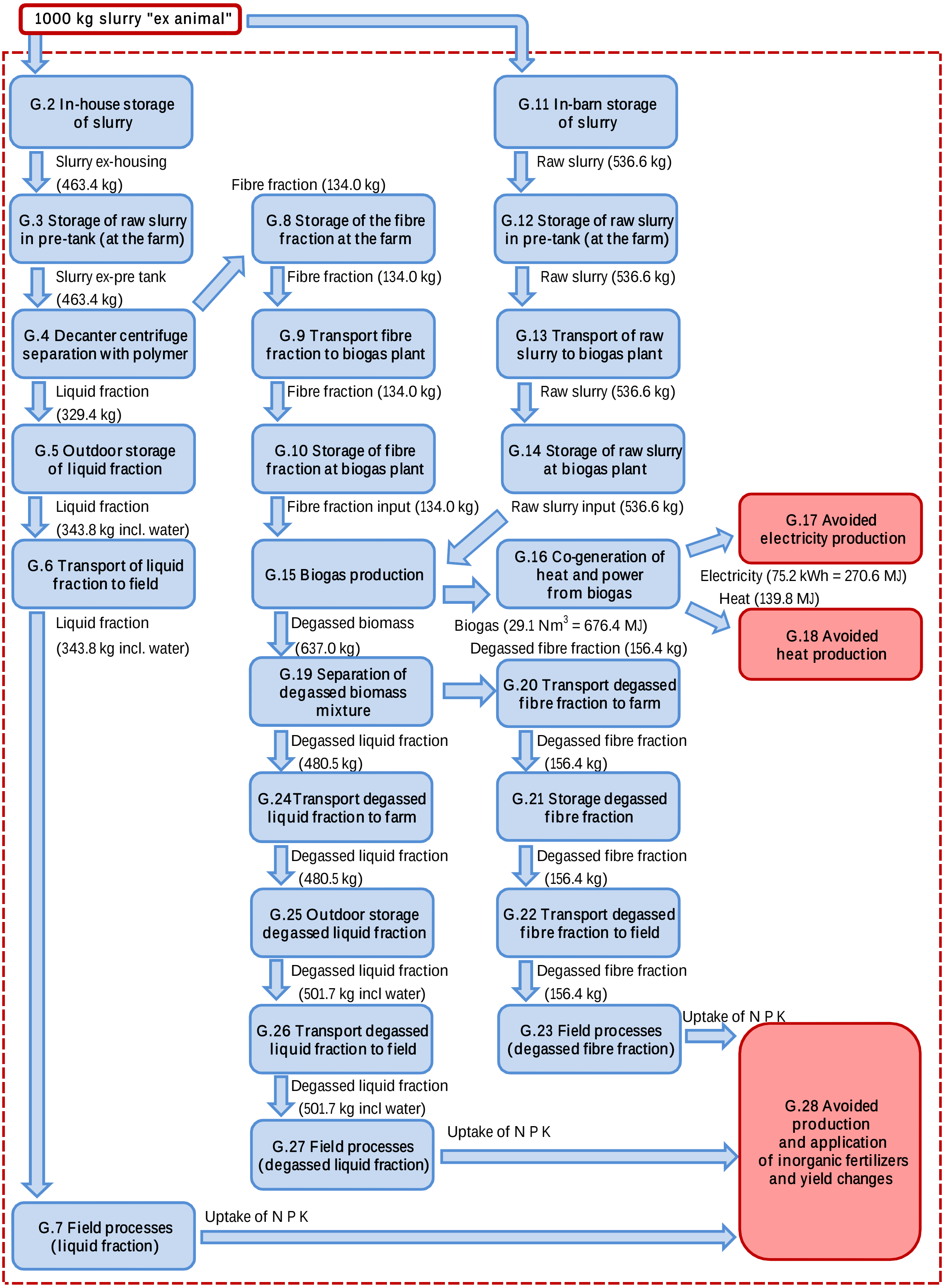
The biogas produced from the cow raw slurry and the fibre fraction mixture is used for co-production of heat and power. The biogas engine used for the generation of heat and power is also considered as a “best available technology”, as the engine used has conversion efficiencies ranking in the highest available range.

After the anaerobic digestion, the resulting degassed slurry is mechanically separated, but without polymer addition. The degassed liquid fraction resulting from this separation process is then stored until it can be used on-field as a fertiliser. The resulting degassed fibre fraction is stored as air-tight covered heap, the heap being covered by a polyethylene plastic sheet. Other options are available for the management of the degassed fibre fraction (e.g. processing it in order to make fibre pellets), but covering was considered as a “best available technology”, as explained in Annex G (section G.21.1).

The processes described and used for this scenario were built in collaboration with Xergi A/S and some of the data used were obtained directly from Xergi A/S (see Annex F). The conclusions made in this section rely on this information, and the authors of this study have not had the possibility of verifying these data.

Figure 5.1 presents the process flow diagram for “Scenario G”. The process numbers in figure 5.1 follows the numbers of the sections in Annex G.

Figure 5.1.
Process flow diagram for "scenario G" – Biogas from raw cow slurry and fibre fraction of mechanical-chemical separation of cow slurry. The process numbers follows the numbers of the sections in annex G



5.2 Results of the Impact Assessment

5.2.1 Overall results of the comparison

Table 5.1 presents the overall environmental impacts from “Scenario G” (biogas from raw cow slurry and fibre fraction from mechanical-chemical separation), and compare them to the environmental impacts from the reference scenario for cow slurry (described in section 3). Figures 5.2 A and 5.2.B illustrate the results presented in table 5.1. Figures 5.2 A and 5.2.B are identical except for the minimum and maximum at the axis. In the case of figure 5.2.B, the minimum and maximum were adjusted in order to present the full impacts covered for the impact “consumption of non-renewable energy resources”. As in section 4, results are presented for soil JB3 only (sandy soil), but a sensitivity analysis assesses the differences in the results that are obtained if another soil type (soil JB6: clay soil) is considered (this is however only performed with the data of Scenario F, see section 8).

As explained in section 4.2.1, the results presented are “characterised” results and are expressed, for each impact categories, relative to the result of the reference scenario. The positive values are the contributions to the environmental impacts and resource consumption by the slurry management scenarios. The negative values are “avoided environmental impacts”.

Results presented in table 5.1 should be interpreted with care in the light of the assumptions and data that were used to obtain them, i.e. the life cycle inventory data presented in Annex G. An attempt to discuss these results based on this focus, impact category per impact category, is presented in sections 5.2.2 to 5.2.11.

Table 5.1.

Scenario G vs A: Contribution of the different processes to each environmental impact categories selected. Results, for each impact category, are expressed in % of the total positive contributions from the reference scenario (considering the 10 years values, when this applies). Soil JB3 (sandy)[1]

Impact Categories	GW (10 y)	GW (100 y)	Acidification	Eutrophication (N) (10 y)	Eutrophication (N) (100 y)	Eutrophication (P)	Ozone formation	Respiratory inorganics	Non-renewable energy	Phosphorus resources
SCENARIO A - cow										
A.2 In-house storage	26.5	26.5	36.6	8.4	8.4	0.0	55.4	34.6	0.0	0.0
A.3 Outdoor storage - elect	0.9	0.9	0.2	0.0[a]	0.0[a]	0.0[a]	0.4	0.3	30.3	0.0[a]
A.3 Outdoor storage	18.2	18.2	10.7	2.6	2.6	0.0	39.0	13.3	0.0	0.0
A.4 Transport to field	1.0	1.0	0.7	0.1	0.1	1.2	1.9	2.7	40.7	0.0[a]
A.5 Field processes	53.4	62.4	51.8	88.9	104.2	98.8	3.3	49.1	29.0	0.0[a]
A.6 N fertiliser	-10.0	-13.4	-9.9	-64.3	-71.2	-2.1	-7.0	-15.0	-211.3	0.0[a]
A.6 P fertiliser	-1.3	-1.3	-3.3	-0.1	-0.1	-138.4	-1.5	-5.3	-60.8	-99.9
A.6 K fertiliser	-0.9	-0.9	-0.4	-0.1	-0.1	-0.9	-1.0	-1.2	-40.0	-0.1
Sum of positive contributions	***100***	***109***	***100***	***100***	***115***	***100***	***100***	***100***	***100***	***0.0[a]***
Sum of negative contributions	***-12***	***-16***	***-14***	***-64***	***-71***	***-141***	***-10***	***-22***	***-312***	***-100***
SCENARIO G										
G.2 + G.11 In-house storage	26.5	26.5	36.6	8.4	8.4	0.0	55.4	34.6	0.0	0.0
G.3 + G.12 Pre-tank storage	0.4	0.4	0.1	0.0[a]	0.0[a]	0.0[a]	0.2	0.1	14.5	0.0[a]
G.4 Separation – elect & equipment	0.3	0.3	0.1	0.0[a]	0.0[a]	0.0[a]	0.1	0.1	8.8	0.0[a]
G.4 Polymer for separation	0.1	0.1	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.1	0.0[a]	4.4	0.0[a]
G.5 Outdoor storage liquid fraction	2.4	2.4	2.5	0.6	0.6	0.0[a]	4.6	3.1	4.1	0.0[a]
Transport (G.6, G.9, G.13, G.20, G.22, G.24, G.26)	1.7	1.7	1.1	0.2	0.2	1.4	3.5	4.0	72.7	0.0[a]
G.7 Field processes (liquid fraction)	6.3	7.8	11.7	21.7	24.6	14.6	0.9	11.3	9.6	0.0[a]
G.8 Storage fibre fraction on-farm	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.1	0.0[a]
G.10 Storage fibre fraction biogas pl.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
G.14 Storage raw slurry biogas plant	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
G.15 Biogas production	2.0	2.0	0.2	0.0[a]	0.0[a]	0.1	2.9	0.3	32.4	0.0[a]
G.16 Co-generation heat and power	19.1	19.1	8.0	2.3	2.3	0.1	32.4	19.2	5.0	0.0[a]
G.17 Avoided electricity production	-18.7	-18.7	-4.6	-0.4	-0.4	-0.7	-9.0	-6.6	-641.1	0.0[a]
G.18 Avoided heat production	-5.6	-5.6	-5.8	-0.3	-0.3	-0.9	-4.3	-7.4	-138.7	0.0[a]
G.19 Separation degassed mixture	0.4	0.4	0.1	0.0[a]	0.0[a]	0.0[a]	0.2	0.1	12.1	0.0[a]
G.21 Storage degassed fibre fraction	0.9	0.9	3.9	0.9	0.9	0.0[a]	0.9	3.6	0.6	0.0[a]
G.23 Field processes (degassed fibre fraction)	16.8	20.4	5.4	9.2	16.2	56.0	0.6	5.3	6.2	0.0[a]
G.25 Outdoor storage (degassed liquid fraction)	4.0	4.0	5.9	1.4	1.4	0.0[a]	7.7	6.8	6.0	0.0[a]
G.27 Field processes (degassed liquid fraction)	12.0	15.9	30.5	56.8	64.3	28.7	1.2	28.5	14.0	0.0[a]
G.28 N fertiliser – production & application on JB3	-10.0	-13.4	-9.9	-64.4	-71.3	-2.1	-7.0	-15.0	-211.5	0.0[a]
G.28 P fertiliser – production & application on JB3	-1.4	-1.4	-3.6	-0.1	-0.1	-149.6	-1.7	-5.8	-65.7	-108
G.28 K fertiliser – production & application on JB3	-1.2	-1.2	-0.5	-0.1	-0.1	-1.3	-1.4	-1.6	-54.5	-0.1
G.28 Yield changes	-0.8	-1.3	-0.8	-3.7	-5.5	-2.8	-0.5	-1.1	-10.3	-1.4
Sum of positive contributions	***93***	***102***	***106***	***102***	***119***	***101***	***111***	***117***	***190***	***0.0[a]***
Sum of negative contributions	***-38***	***-42***	***-25***	***-69***	***-78***	***-157***	***-24***	***-38***	***-1122***	***-110***

[1] The number of digits is not an expression of the uncertainty. All numbers are all rounded and accordingly, if the reader calculates the sum or the difference, it might vary slightly from the numbers shown in the table.

[a] This number is not a zero value.

Figure 5.2.A
Overall environmental impacts for the selected impact categories – scenario G vs scenario A. Dairy cow slurry management. Soil type JB3. 10 and 100 years time horizon for global warming and for aquatic eutrophication (N). Axis ranging from -180 to 140.

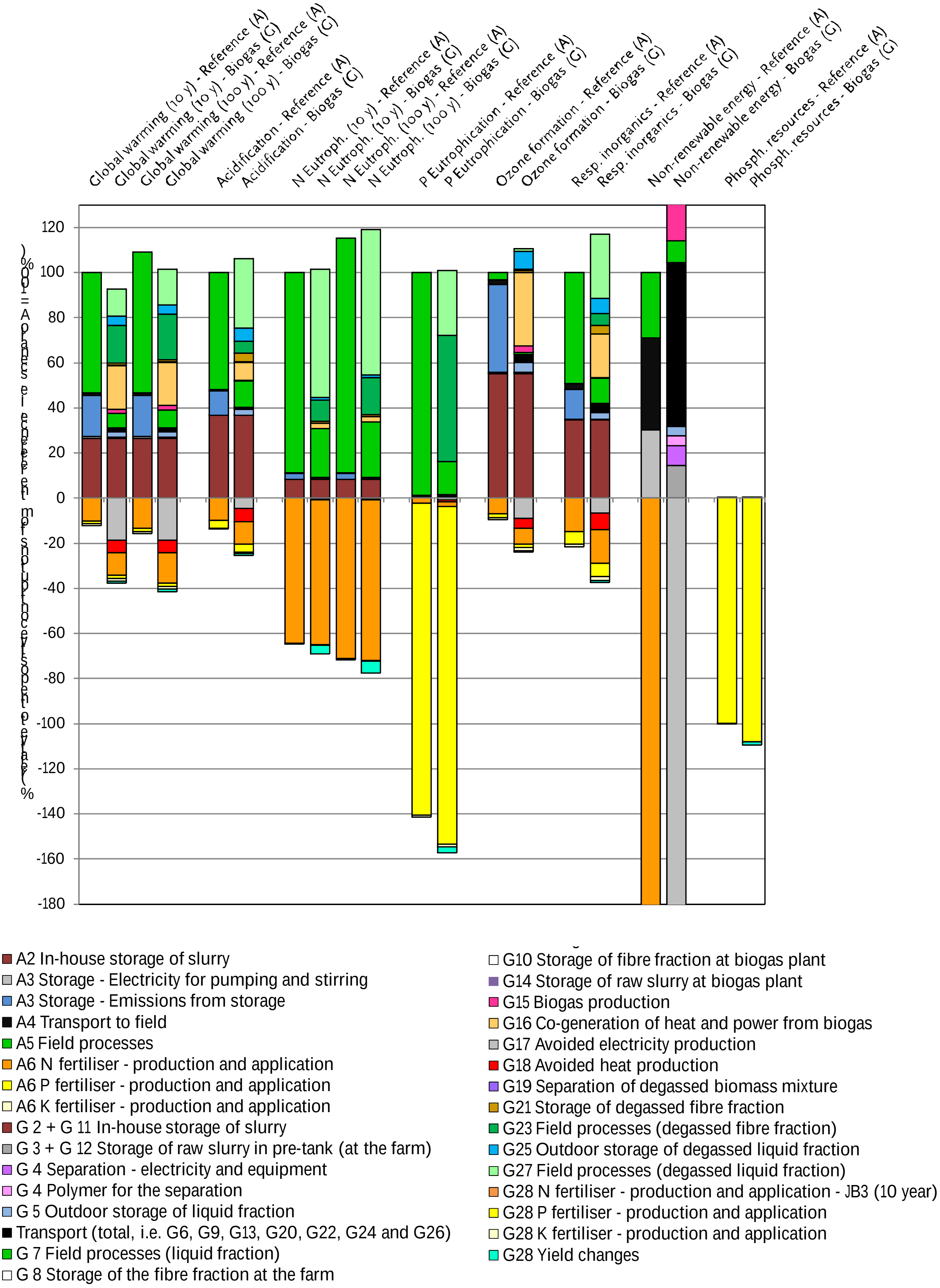
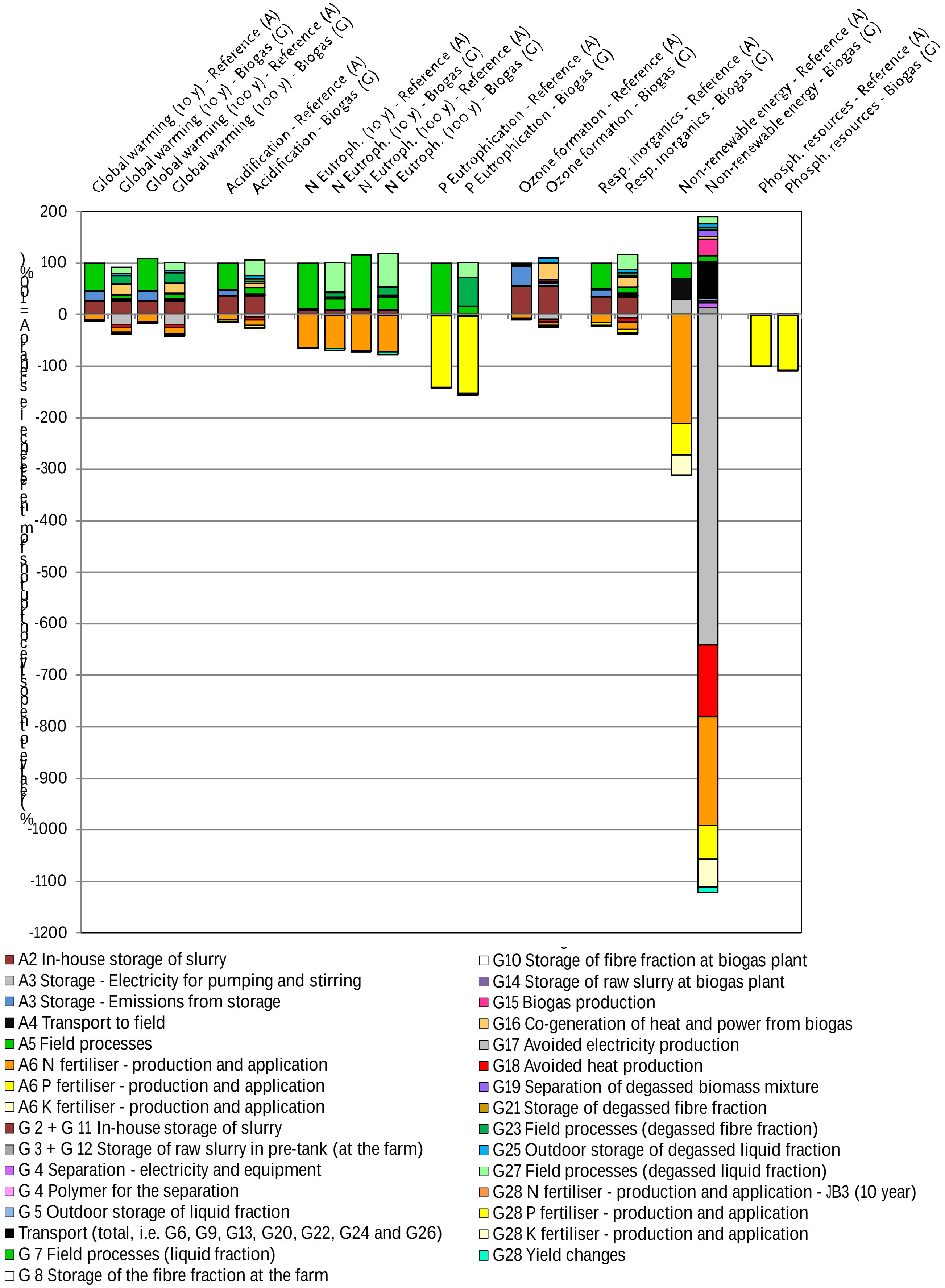


Figure 5.2.B
Overall environmental impacts for the selected impact categories – scenario G vs scenario A. Dairy cow slurry management. Soil type JB3. 10 and 100 years time horizon for global warming and for aquatic eutrophication (N). Axis ranging from -1200 to 200.



In the following sections, the benefits (and shortcomings) of producing biogas as described in Scenario G instead of the reference slurry management are discussed in details for each impact categories.

5.2.2 Global warming

As for Scenario F (which is the same as the present scenario, but with pig slurry), there are two main processes contributing to global warming:

- In-house storage of slurry
    - Scenarios A and G: This process represents about 27 % of the total positive contributions to global warming from the reference scenario.
- Field processes
    - Scenario A: This process represents 53 % of the total positive contributions to global warming from the reference scenario (and 62 % if the 100 years values are considered for C horizon in the field).
    - Scenario G: This process (for the aggregation of all organic fertilisers: liquid fraction, degassed fibre fraction and degassed liquid fraction) represents 35 % of the total positive contributions to global warming from the reference scenario (and 44 % if the 100 years values are considered for C horizon in the field).

As for Scenario F, the high contribution from the in-house storage is due to CH_4 emissions. There are only three gases contributing to the global warming potential of this process: CH_4 (76 %), N_2O (14 %) and CO_2 (10 %). The proportions shown in parenthesis are for a 10-years value as regarding the C horizon in the field.

Important emissions from CH_4 were expected for this process, as the anaerobic conditions for slurry stored below animal floors favour CH_4 formation more than the formation of other greenhouse gases. Yet, the high absolute contribution from CH_4 is due to a potentially conservative methodological choice, as detailed in section 4.2.2.

For Scenarios A and G, the contribution of field processes to global warming potential is dominated by biogenic CO_2 (due to C applied emitted as CO_2). In the case of Scenario G, biogenic CO_2 represents 73 % of the positive contributions to global warming from field processes, while N_2O represents 25 %. The contribution to global warming from field processes caused by fossil CO_2 emissions (due to diesel combustion) is 2 %. In fact, there are other gases involved, but their relative contribution is rather insignificant (and not reflected when the percentages are expressed with no decimal place). The biogenic CO_2 emitted in the field is lower for Scenario G than Scenario A (83 kg CO_2 equivalent in Scenario G as compared to 132 kg CO_2 equivalent in Scenario A). This is simply because, in the case of Scenario G, this biogenic CO_2 was emitted in earlier stages, mostly during the co-generation of heat and power. In that case, however, heat and electricity were produced together with the emission.

For Scenario G, it can also be highlighted that the biogenic CO_2 emissions from field processes are the highest with the application of the degassed fibre fraction (49 kg CO_2equivalent) as compared to the degassed liquid fraction

(24 kg CO_2equivalent) and the liquid fraction (10 kg CO_2equivalent), respectively. This is because the fibre fraction has the highest C content per functional unit (table 5.2), and because it was considered that, on both a 10 and a 100 years horizon for C, most of the "slowly degradable" portion of the C is also degraded, thus contributing to CO_2 emissions.

As explained in section 4.2.2, high contributions to global warming potential from N_2O were expected for field processes, as N_2O has a 100-years global warming potential of 296 kg CO_2 equivalent per kg N_2O, based on the EDIP method (which is in turn based on IPCC, 2001). Because, for all fractions applied to field, the emission of N_2O were estimated based on the IPCC methodology (IPCC, 2006), the N_2O emissions are function of the N content in the applied slurry. Table 5.2 shows the C and N content of the different fractions involved in scenario A and G.

Table 5.2.
C and N content of the different organic fractions involved in Scenario A and G

Material	Amount per functional unit (kg)	N in material (kg)	C in material (kg)	C/N	N per functional unit	C per functional unit
Scenario G						
Liquid fraction	343.8	4.07	13.44	3.30	1.40	4.62
Degassed fibre fraction	156.4	6.21	111.0	17.87	0.97	17.36
Degassed liquid fraction	501.7	7.36	22.1	3.00	3.69	11.09
Scenario A - cow						
Slurry ex-storage	1044	6.02	45.2	7.51	6.28	47.19

The degassed liquid fraction thus has the highest contribution to N_2O, as it has the highest N content per functional unit, followed by the liquid fraction and the degassed fibre fraction. The contribution of N_2O to global warming from field processes is higher for Scenario A than Scenario G (29 kg CO_2 equivalent in Scenario G and 40 kg CO_2 equivalent in Scenario A). If the emissions of N_2O-N represent 3 to 5 % of the N applied as suggested by Crutzen et al. (2008) rather than the 1 % of the IPCC methodology (IPCC, 2006) as used in this study, the global warming contribution from field processes would be much more important, as a small increment of N_2O has huge impacts on global warming potential.

The co-generation of heat and power from biogas also represents, in the case of Scenario G, a rather significant contribution to global warming, representing 19 % of the total positive contributions to global warming from the reference scenario. This, as explained in section 4.2.2, is mainly due to the combustion gases from burning the biogas (i.e. CH_4 and CO_2) in the biogas engine. The production of biogas itself (process G.15 of Annex G) represents a minor share of the contribution to global warming potential, with only 2% of the total positive contributions to global warming from the reference scenario.

Another interesting observation to highlight from figure 5.2.A is the benefit on global warming contribution obtained through storing the slurry as separated (and degassed) fractions rather than as raw slurry. While storage of raw slurry represents 18 % of the total positive contributions to global warming from the reference scenario, the contribution from separated liquid is 2.4 %, and it is 0.9 % and 4 % for the degassed fibre fraction and the degassed liquid fraction, respectively. This is mainly because of lower CH_4 emissions due to the separation (and digestion) of the VS, as explained in section 4.2.2.

Finally, as it can be observed from figure 5.2.A, the contributions to global warming from the use of electricity, the use of polymer for separation and the transportation are rather negligible.

If both slurry management assessed allow to avoid the use of inorganic fertilisers (N, P and K), the biogas scenario also allow to avoid the production of marginal heat and electricity (see definition section 2.3). Avoiding the production of marginal electricity (a mix of wind, coal and natural gas, see table 2.1) by the use of the electricity produced from the biogas allow considerable benefits in terms of global warming contribution avoided. This corresponds to an “avoidance” of 19 % of the total positive contributions to global warming from the reference scenario. Avoiding the production of marginal heat (i.e. 100 % coal, see table 2.1) through the heat produced from the biogas also has a positive impact on global warming contribution (an avoidance of about 6 % of the total positive contributions to global warming from the reference scenario).

Avoiding the production and use of inorganic fertilisers (particularly N, but also P and K to a lesser extent) through the use of the produced organic fertilisers contribute, for both Scenario A and Scenario G, to the avoidance of global warming potential, and this avoidance is in the same order of magnitude for both scenarios. Avoiding the production and use of inorganic N avoids the production of N_2O which represents the main reason for the magnitude of avoided contribution to global warming for this process. As explained in Annex G (section G.28.2), the amount of N avoided is the same in Scenario G than in the reference scenario as the “rule of conservation” (Gødskningsbekendtgørelsen, 2008) was applied to calculate the amount of inorganic N substituted by each organic fractions. The amount of inorganic P and K substituted in Scenarios A and G are different, but this does not affect the avoided contribution to global warming, as they are in the same order of magnitude for both scenarios. In the case of avoided P and K, the benefits are mostly due to the avoided fossil CO_2.

Similarly, the higher wheat production obtained through higher yields in Scenario G also allows to avoid contribution to global warming (mostly through N_2O), though this is rather small.

Overall, when the “deductions” from the avoided contributions to global warming are accounted for, managing the cow slurry as described in Scenario G allows a net reduction of 107 kg CO_2 equivalent as compared to the reference scenario (figure 5.3).

Table 5.3 summarises, for selected processes, the contribution of the main contributing substances to global warming, for both Scenario A and G.

Table 5.3.
Scenario G vs A: Contribution of the main contributing substances to global warming for selected processes. **All values in kg CO_2 equivalent**. Soil JB3 (sandy).[1]

Processes		CH_4	Biogenic CO_2 (field)	N_2O	CO_2 (fossil or biogenic not from field processes)	Total emission (kg CO_2 equivalent) for the process
Scenario A (cow)						
In-house storage		65.55	0	9.30	11.60	86.45
Outdoor storage		38.64	0	16.55	4.21	59.40
Field processes		0	131.96	39.83	2.20[b]	174.08[a]
Scenario G						
In-house storage		65.55	0	9.30	11.60	86.45
Outdoor storage	Liquid fraction	3.23	0	3.84	0.23	7.68[a]
	Degassed fibre fraction	0.92	0	0.47	1.23	2.78[a]
	Degassed liquid fraction	5.56	0	6.55	0.4	13.08[a]
Field processes	Liquid fraction	0	10.42	9.26	0.72[b]	20.43[a]
	Degassed fibre fraction	0	48.54	5.72	0.47[b]	54.75[a]
	Degassed liquid fraction	0	24.03	14.01	1.06[b]	39.14[a]
Biogas production		3.12	0	0.03	2.78[b]	6.40[a]
Co-generation heat and power		5.03	0	0.03	56.55	62.31[a]
Avoided electricity production		0	0	-0.63	-55.10[b]	-60.83[a]
Avoided heat production		0	0	-0.07	-17.06[b]	-18.22[a]

[1] The number of digits is *not* an expression of the uncertainty.
[a] The balance is from other global warming contributing substances not presented in this table.
[b] Fossil CO_2

Managing cow slurry as described in scenario G appears as an interesting mitigation strategy as regarding the efforts to reduce the global warming impacts.

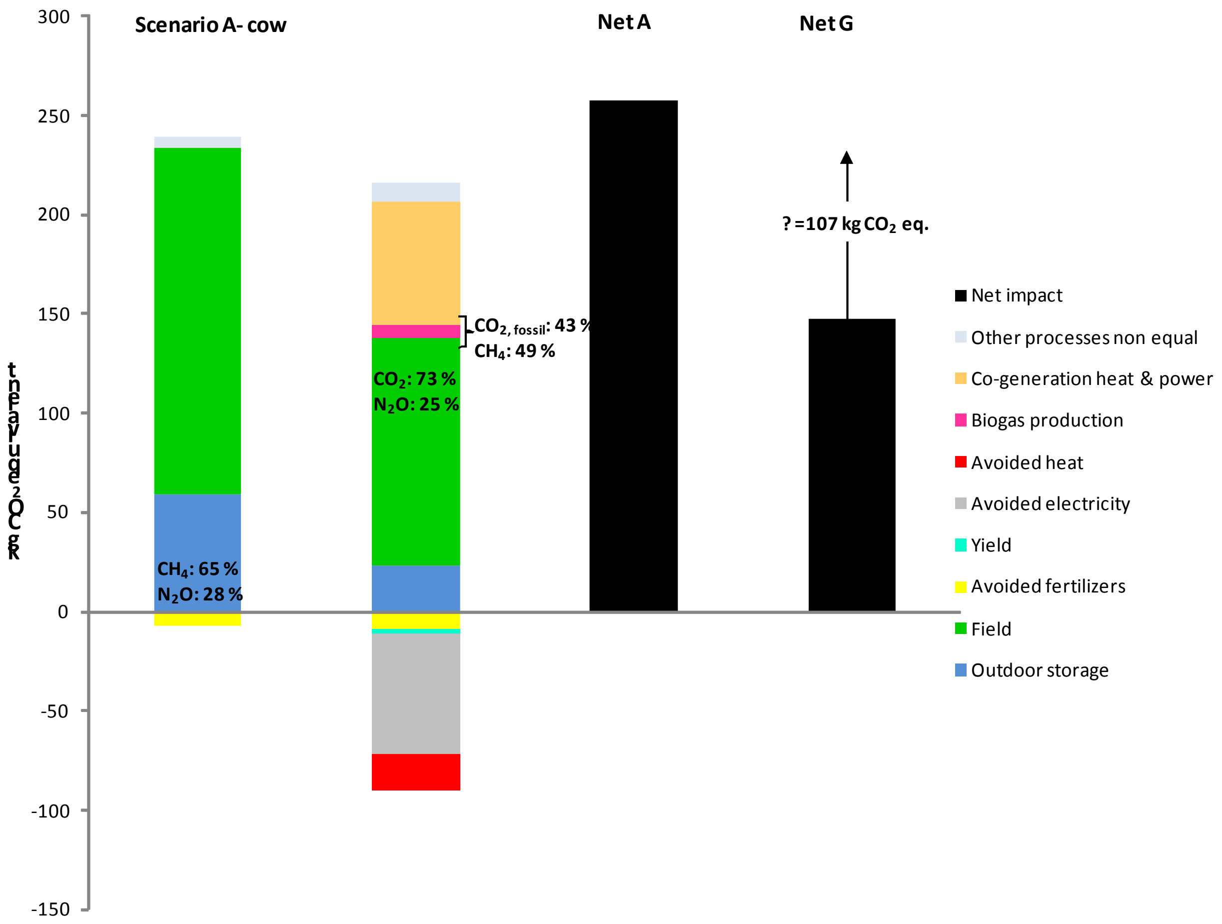
The major results as regarding global warming can be summarised as:

- Overall, managing the slurry as in Scenario G allows, based on the reference scenario considered, to reduce significantly the contributions to global warming from cow slurry management.
- There are 2 major hot spots regarding global warming:
    - In-house storage of slurry. The main contributor is CH_4.
    - Field processes. The main contributor is CO_2 due to the application of the different slurry fractions. The contribution to global warming from field process is much lower in the case of Scenario G as compared to Scenario A.
- Storing slurry in separated phases (with the separation efficiencies considered in Scenario G) has considerable benefits on global warming contribution as compared to storage of raw slurry.
- The contributions to global warming from the use of electricity, the use of polymer for separation and the transportation are rather negligible in both scenarios.
- Both scenarios allow avoiding the contributions to global warming from the production of inorganic N, P and K fertilisers in similar magnitude.
- Scenario G allows avoiding the production of marginal heat and electricity, which has considerable benefits on global warming contributions. Avoided wheat production resulting from yield increases in Scenario G also contribute to additional avoided

contributions to global warming, though the magnitude of it is rather small.

This information is summarised in figure 5.3. This figure presents the contribution to climate change of Scenario A and G only for the processes that are not equal between A and G (i.e. in-house storage and avoided N fertiliser are not included). All processes are presented; the category labelled “other processes non equal” represents the aggregation of all processes not presented in the legend.

Figure 5.3.
Comparison of Scenario G vs Scenario A for global warming including carbon sequestration, for processes differing between A and G only. Soil JB3, 10 years values.



5.2.3 Acidification

The contribution to acidification is dominated by 2 processes:

- Field processes:
    - Scenario A: This represents about 52 % of the total positive contributions to acidification from the reference scenario.
    - Scenario G: This represents about 48 % of the total positive contributions to acidification from the reference scenario.
- In-house storage: For both scenarios, this process represents about 37 % of the total positive contributions to acidification from the reference scenario.

The main contributing substance to acidification from field processes is NH_3, accounting for 98 % of the contributions from this process from both scenarios.

In Scenario G, the highest potential to acidification from the field processes comes from the application of the degassed liquid fraction (64 %), followed by the application of the liquid fraction (25 %) and the degassed fibre fraction (11 %). The NH_3 emissions for the degassed liquid fraction were evaluated with the same estimation as for raw slurry, i.e. as a function of the TAN in the raw slurry. This approach was used as digestion affects both factor promoting and reducing the propensity for volatilisation, as discussed in section 4.2.3 of this report and section G.27.3 of Annex G. If factors reducing the propensity for volatilisation predominate over those promoting it, then the estimation for ammonia emissions would be slightly overestimated for the degassed liquid fraction. This would have some influence but it would not change the overall results of the comparison. For example, cutting the actual ammonia emissions from the digested liquid fraction of 50 % would yield a total acidification potential from the field processes of 14 m^2 unprotected ecosystem, as compared to 21 m^2 as it is now. As a comparison, the in-house storage has an acidification potential of 16 m^2 unprotected ecosystem.

As described in Annex G, there are no differences in the in-house storage between Scenario A and G. The main contributing substance to acidification for the in-house storage of slurry is NH_3, contributing to 98 % of the total acidification potential for this process. The other contributor to acidification from in-house slurry storage is NO_x, with the remaining 2 % of the total acidification potential for this process.

Apart from the in-housing slurry storage and the field processes, “co-generation of heat and power from the biogas” and “outdoor storage” (aggregated for all fractions) can be distinguished as contributors to acidification for Scenario G, though their extent is much lower. For the “co-generation of heat and power”, the main contributor (91%) to acidification from the process is NO_X. This is emitted during the combustion of biogas in the biogas engine. The process “co-generation of heat and power” represents 8.0 % of the total positive contributions to acidification from the reference scenario.

The storage of slurry represents 12 % of the total positive contributions to acidification from the reference scenario. The main contributor to acidification from the storage processes is NH_3 (88 %), but there are also some contributions from NO_X (12 %). Among the different fractions to store, the degassed liquid fraction has the highest contribution to acidification followed by the degassed fibre fraction and the liquid fraction. For all fractions, NH_3emissions were estimated as a function of the N content in it (NH_3-N = 2 % of the N content for both liquid fractions and 5.75 % for fibre fraction, see Annex G). The N content per functional unit for stored degassed liquid is higher (3.83 kg N per 1000 kg slurry ex-animal) than for the other fractions (1.47 kg N per 1000 kg slurry ex-animal for the liquid fraction and 1.03 kg N per 1000 kg slurry ex-animal for the degassed fibre fraction), explaining the highest emissions for the storage of that fraction (table 5.2). The estimate used for the fibre fraction (5.75 %) is lower than the estimate recommended by Hansen (2009) (i.e. 13 %: see Annex G). Therefore, the emissions of NH_3 from the fibre fraction and consequently the contribution to acidification may be higher in reality than as estimated in this project.

As discussed in section 4.2.3, the storage of the fibre fraction at the farm (process G.8), just before it is sent to the biogas plant, was assumed to be without any losses, due, among others, to the temporal nature of this process (see section G.8 of Annex F). Yet, as mentioned in section 4.3.2, NH_3 from separated fibre fraction of animal slurries is recognised as a “hot spot” from slurry management involving separation, so this “no losses” assumption may have contributed to underestimate the overall acidification potential of Scenario G.

The contribution to acidification from transport, use of electricity and use of polymer for separation are rather negligible.

Both scenarios allow avoiding the use of inorganic fertilisers and this contributes, in the two cases, to avoid the same magnitude of acidification potential. However, Scenario G also contributes to avoid the production of marginal heat and marginal electricity, which is translated by an additional credit on the acidification potential (see figure 5.2.A). For both avoided marginal heat and electricity, the main avoided contributor to acidification is SO_2. The higher yield in Scenario G contributes to avoid the production of a given amount of crop (here modelled as wheat) and consequently the related contribution to acidification from it. Yet, this is rather small, as it can be seen in table 5.1 and figure 5.2.A.

Overall, when the “deductions” from the avoided contributions to acidification are accounted for, managing cow slurry as described in Scenario G allows a net reduction of 2.36 m^2 area of unprotected ecosystem (UES) as compared to the reference scenario (figure 5.4).

Table 5.4 summarises, for selected processes, the contribution of the main contributing substances to acidification, for both Scenario A and G.

Table 5.4.
Scenario G vs A: Contribution of the main contributing substances to acidification for selected processes. **All values in m^2 unprotected ecosystem (UES)**. Soil JB3 (sandy).[1]

Processes		NH_3	NO_X	SO_2	Total emission (m^2 UES) for the process
Scenario A (cow)					
In-house storage		15.45	0.40	0	15.85
Outdoor storage		3.65	0.96	0	4.61
Field processes		22.00	0.35	0.06	22.41[a]
Scenario G					
In-house storage		15.45	0.40	0	15.85
Outdoor storage	Liquid fraction	0.825	0.226	0.008	1.060[b]
	Degassed fibre fraction	1.668	0.014	0.002	1.683[a]
	Degassed liquid fraction	2.160	0.377	0.011	2.550[b]
Field processes	Liquid fraction	4.94	0.10	0.02	5.06[a]
	Degassed fibre fraction	2.24	0.06	0.01	2.32[b]
	Degassed liquid fraction	13.05	0.13	0.03	13.21[a]
Biogas production		0.001	0.027	0.062	0.100[b]
Co-generation heat and power		0.00[c]	3.145	0.306	3.453[b]
Avoided electricity production		-0.02	-0.52	-1.22	-1.97[b]
Avoided heat production		-0.01	-0.37	-1.66	-2.50

[1] The number of digits is *not* an expression of the uncertainty.
[a] This includes other contributing substances which are not reflected when contributions are presented with 2 decimal places.
[b] The balance is from other acidification contributing substances not presented in this table.
[c] This is not a zero value.

Based on these results, it can be concluded that managing slurry as described in Scenario G does not allow significant environmental benefits as regarding acidification potential, as compared to the reference slurry management.

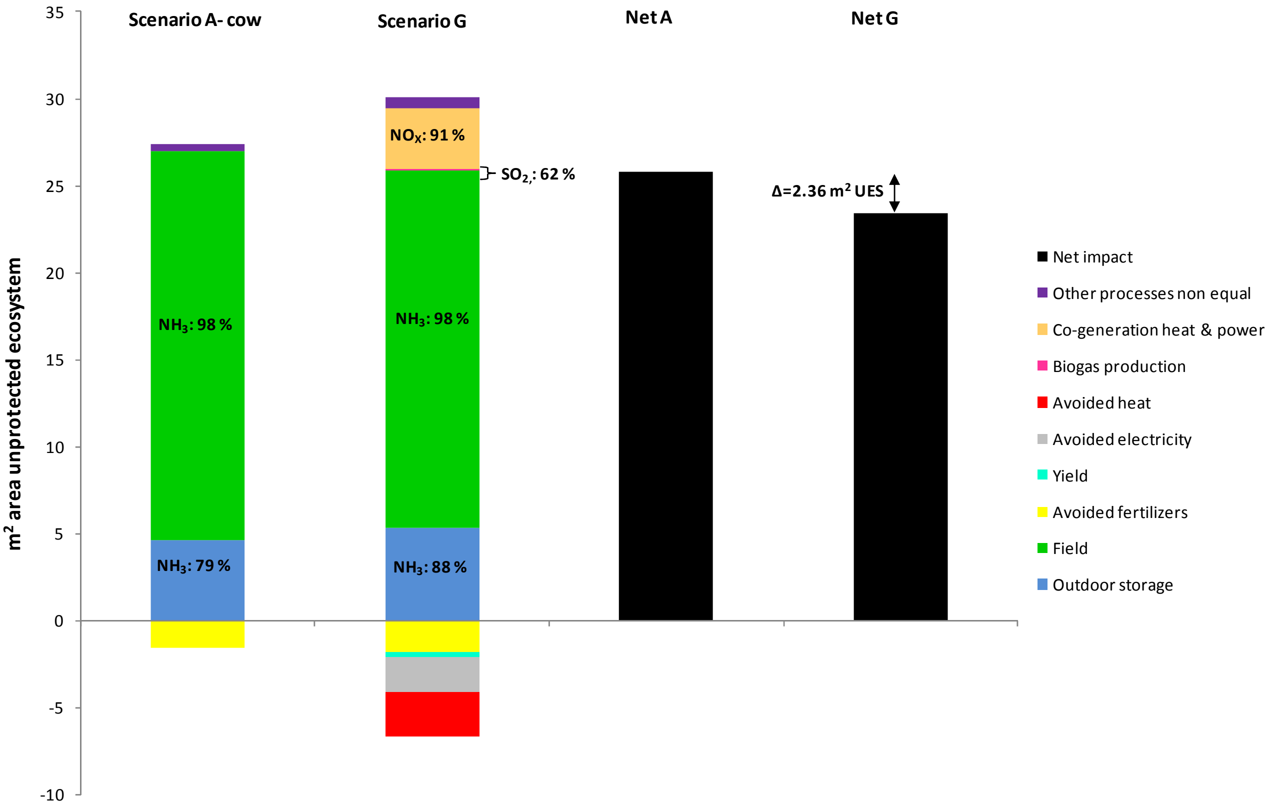
The major results as regarding acidification can be summarised as:

- Overall, managing the slurry as in Scenario G does not allow significant environmental benefits as regarding acidification potential.
- There are 2 major hot spots are regarding acidification:
    - In-house storage of slurry. The main contributor is NH_3.
    - Field processes. The main contributor is NH_3.
- The overall contribution to acidification from outdoor slurry storage is greater for Scenario G and NH_3 is the main contributor. This is mostly due to the storage of the degassed fibre fraction, even though the degassed fibre fraction is not the highest absolute contributor among the 3 fractions to store (because of the overall amount per functional unit).
- The contributions to acidification from the use of electricity, the use of polymer for separation, and the transportation are rather negligible in both scenarios.
- Both scenarios allow avoiding the contributions to acidification from the production of inorganic N, P and K fertilisers in similar magnitude. Scenario G allows to avoid the production of marginal heat and electricity, which has additional benefits on acidification contributions. In a much smaller extent, the avoided wheat production resulting from increased yield also contributes to avoid contributions

to acidification if Scenario G is implemented as compare to Scenario A.

This information is summarised in figure 5.4. This figure presents the contribution to acidification of Scenarios A and G only for the processes that are not equal between A and G (i.e. in-house storage and avoided N fertiliser are not included). All processes are presented; the category labelled “other processes non equal” represents the aggregation of all processes not presented in the legend.

Figure 5.4.
Comparison of Scenario G vs Scenario A for acidification, for processes differing between A and G only. Soil JB3, 10 years values.



5.2.4 Aquatic eutrophication (N)

This impact category is, for both scenarios, dominated by field processes. Field processes represent, for Scenario A, 89 % of the total positive contributions to eutrophication (N) from the reference scenario (10 years value for C horizon in the field). For Scenario G, field processes represent 88 % of the total positive contributions to eutrophication (N) from the reference scenario (10 years value for C horizon in the field). In both cases, the main contributing substance is N leaching through soil. For Scenario G, N leaching through soil represents about 88 % of the contributions to N-eutrophication from field processes, and NH_3 represents about 12 % to it.

The use of the degassed liquid fraction in the field has the highest contribution to N-eutrophication as compared to the liquid fraction and the degassed fibre fraction. This is because, there is, for the the degassed liquid fraction, a greater N content per functional unit (3.69 kg N per 1000 kg slurry ex-animal) as compared to the liquid fraction (1.40 kg N per 1000 kg slurry ex-animal) and the degassed fibre fraction (0.97 kg N per 1000 kg slurry ex-animal) (table 5.2).

In-house storage of slurry represents about 8 % of the total positive contributions to eutrophication (N) from the reference scenario (for the 10 years values for C horizon in the field), and this is mostly due to NH_3 (97 %). All other processes are contributing rather insignificantly.

The production (and use) of inorganic N is avoided in both scenarios, and this contribute to a quite important avoidance of N-eutrophication to occur (64 % of the total positive contributions to N-eutrophication from the reference scenario, for both Scenario A and Scenario G and for the 10 years values). The avoided production of heat and electricity in Scenario G has a minor impact on the N-eutrophication potential avoided.

The avoided wheat production resulting from higher yield in Scenario G also contributes to avoid eutrophication-N potential, but the importance of this is rather small, as it can be visualised from figure 5.2.A.

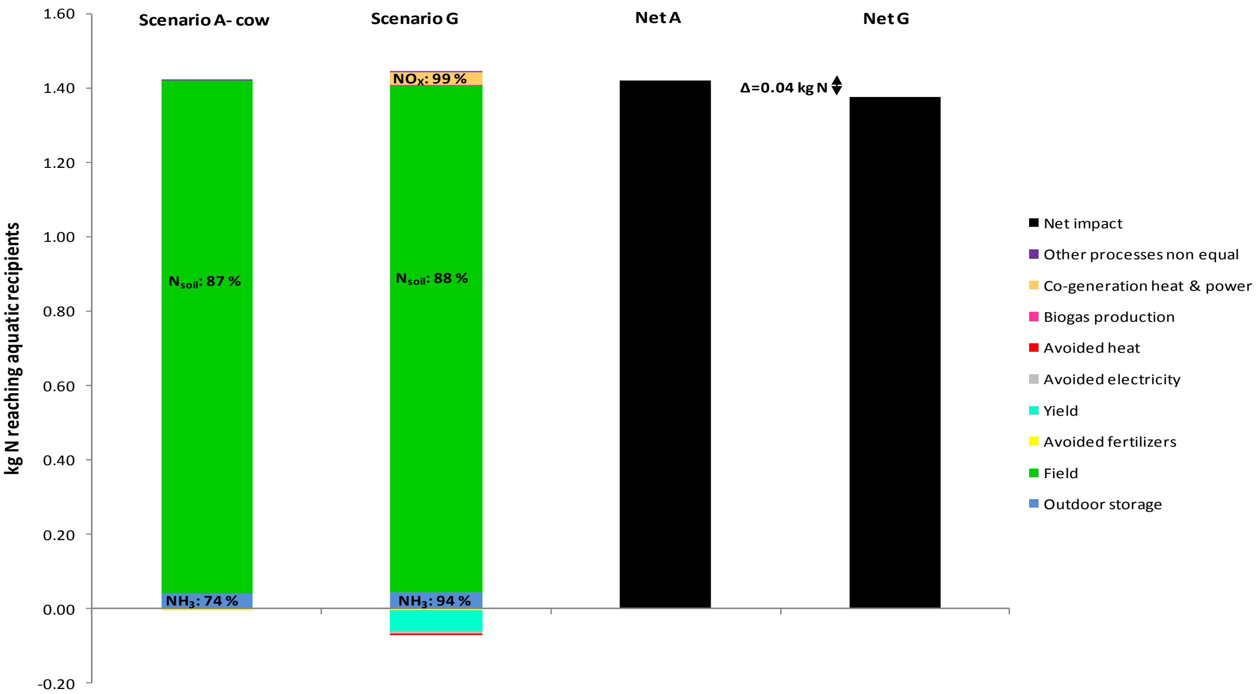
Overall, when the “deductions” from the avoided contributions to N-eutrophication are accounted for, the difference between managing the slurry as described in Scenario G as compared to the reference slurry management allows a net difference of 0.04 kg N reaching aquatic recipients, however, when accounting for uncertainties, this benefit could be reduced to 0 (figure 5.10.A). This is for the 10 years value for C horizon in the field.

The major findings as regarding N-eutrophication potential can be summarised as:

- Managing slurry as described in Scenario G does allow a small benefit as regarding aquatic N-eutrophication, as compared to slurry management described in the reference scenario. This benefit may however be negated considering the values of the uncertainty range.
- Field process is the main hot spot as regarding aquatic N-eutrophication: N leaching through soil is the main contributing substance to N-eutrophication for this process.
- In-house storage, in both scenarios, also has some contributions to aquatic N-eutrophication, and this is mainly due to NH_3 emissions.
- Avoiding inorganic N fertilisers to be produced allows, in both scenarios, to avoid significant contribution to aquatic N-eutrophication.

This information is summarised in figure 5.5. This figure presents the contribution to N-eutrophication of Scenarios A and G only for the processes that are not equal between A and G (i.e. in-house storage and avoided N fertiliser are not included). All processes are presented; the category labelled “other processes non equal” represents the aggregation of all processes not presented in the legend.

Figure 5.5.
Comparison of Scenario G vs Scenario A for aquatic N-eutrophication, for processes differing between A and G only. Soil JB3, 10 years values.



5.2.5 Aquatic eutrophication (P)

For aquatic P-eutrophication, there is also one major hot spot: field processes, contributing to this environmental impact in approximately the same extent in both Scenario A and Scenario G. In both scenarios, it represents about 99 % of the total positive contributions to eutrophication (P) from the reference scenario, meaning that all other processes contribute rather insignificantly to this environmental impact. For field processes in both scenarios, P leaching to soil contributes to 99 % of the substances contributions to this impact category.

For Scenario G, it can be highlighted that, for the field processes, the degassed fibre fraction contribute to about 56 % of the total positive contributions to eutrophication (P) from the reference scenario, while it is 29 % for degassed liquid fraction and 15 % for the liquid fraction. For all organic fertilisers involved (liquid fraction, degassed fibre fraction and degassed liquid fraction), it was considered that P leaching to soil (the main contributor to P-eutrophication for field process) corresponds to 10 % of the P applied to field, and 6 % of this has the possibility to reach aquatic recipients (based on Hauschild and Potting, 2005). This is detailed in sections G.7, G.23 and G.27 of Annex G. The differences obtained between the two liquid fractions therefore reflect the efficiency of the first separation to separate the P in the solid fraction, thus explaining a much lower contribution from the liquid fraction.

The assumption used to estimate P leaching involves some uncertainties, as detailed in Wesnæs et al. (2009) (section 3.4.6 and section A.5.6, among others). In fact, the P actually reaching the aquatic recipients is also a function of the soil type and of the P already present in the soil. However, the purpose of the present study is comparative, and the same assumptions have been applied to both scenarios. In this perspective, the conclusions of this study are reliable, i.e. P leaching through soils is the main contributor to aquatic P-eutrophication for both scenarios. However, the “real” magnitude of P leaching through aquatic recipient (in kg P per 1000 kg slurry ex-animal) may be different than as presented in Annex A and G of the present study.

Avoiding inorganic P fertilisers to be produced and applied contributes, in both scenarios, to an important share of the avoidance of aquatic P eutrophication. This effect is however more important for Scenario G. This is because in Scenario G, the P is not applied in excess as most of it is applied via the degassed fibre fraction, which is applied on a field where P is the limiting nutrient for crop growth. Therefore, all organic P applied in Scenario G corresponds to avoided inorganic P, as compared to the reference scenario where only a share of the organic P substitutes inorganic P, the rest being pure excess. To a much smaller extent, avoiding N and K fertilisers to be used and produced also allow to avoid P-eutrophication potential.

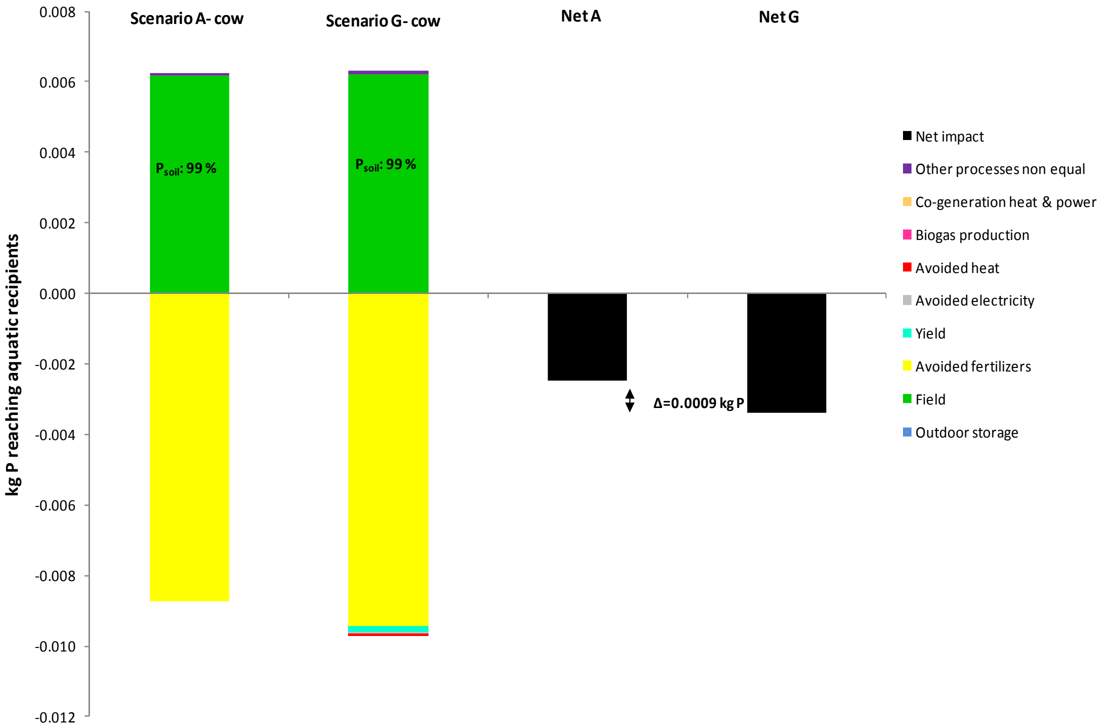
Similarly to N-eutrophication, the avoided wheat production resulting from higher yields in Scenario G has here some importance, the avoidance of P-eutrophication representing about 3 % of the total positive contributions to P-eutrophication from the reference scenario.

Avoiding the production of marginal heat and electricity has, for Scenario G, only a minor effect on the avoidance of P-eutrophication potential.

One interesting point about P eutrophication potential is that it is an impact category where the net contributions are negative. This means that whether the slurry is managed as in Scenario A or G, the fact of avoiding inorganic P fertilisers to be produced/used overcome the contribution to P-eutrophication from managing the slurry itself. This statement, however, is only true if 1 kg P in slurry contributes equally to P-eutrophication as 1 kg P in mineral fertiliser, which might not be the case.

Overall, when the “deductions” from the avoided contributions to P-eutrophication are accounted for, there is a gain in managing the slurry as described in Scenario G as compared to the reference slurry management. This is illustrated in figure 5.6.

Figure 5.6.
Comparison of Scenario G vs Scenario A for aquatic P-eutrophication, for processes differing between A and G only. Soil JB3, 10 years values.



The major results as regarding P-eutrophication potential can be summarised as:

- Managing slurry as described in Scenario G results in a gain as compared to Scenario A.
- Field process is the main hot spot as regarding aquatic P-eutrophication: P leaching is the main contributor to this process.

5.2.6 Photochemical ozone formation (“smog”)

In both scenarios, there are 2 main hot spots for photochemical ozone formation. Common to both scenarios is:

- In-house storage, representing about 56 % of the total positive contributions to photochemical ozone from the reference scenario.

For Scenario A, outdoor storage is also a hot spot for ozone formation, representing 39 % of the positive contributions from the reference scenario. For Scenario G, the co-generation of heat and power is the second hot-spot, representing 32 % of the positive contributions from the reference scenario.

In the case of in-house storage, the main contributor is CH_4, which represents about 94 % of the contribution to ozone formation for this process. The overall emissions of CH_4 from in-house may have been overestimated, as discussed in section 4.2.2. The alternative MCF value for estimating CH_4 from in-house slurry storage (see description section 4.2.2) would lead to a reduction of 0.06807 person*ppm*h, representing a reduction of about 76 % of the ozone formation potential. In spite of this, CH_4 would remain the main contributor to ozone formation for in-house storage.

For co-generation of heat and power, the main contributor is NO_x, representing about 85 % of the contribution to ozone formation for this process. This is emitted during the combustion of biogas in the biogas engine.

In Scenario A, CH_4 emission is the main contributing substance (78 %) to ozone formation impact for the outdoor storage process. As it can be observed in table 5.1, slurry storage is much less significant for Scenario G than Scenario A. This is due, as described in section 4.2.2, to the lower VS content of separated and degassed slurry, thus involving a much lower potential for CH_4 emissions. This again highlights the positive effect of slurry separation and digestion as regarding CH_4 emissions during slurry storage.

The production of biogas itself also contributes to photochemical ozone formation through the small amount of CH_4 leakages that was assumed (CH_4 represents 84 % of the contributions for this process).

Avoiding inorganic fertilisers to be produced (N, but to a smaller extent P and K) also contribute to reduce the contribution to ozone formation, in similar magnitude for both scenarios. However, the avoided production of marginal heat and electricity in Scenario G contribute to “extra” avoidance of contribution to photochemical ozone. So does the avoided wheat production induced by increased yield, but this represents a rather small avoided contribution.

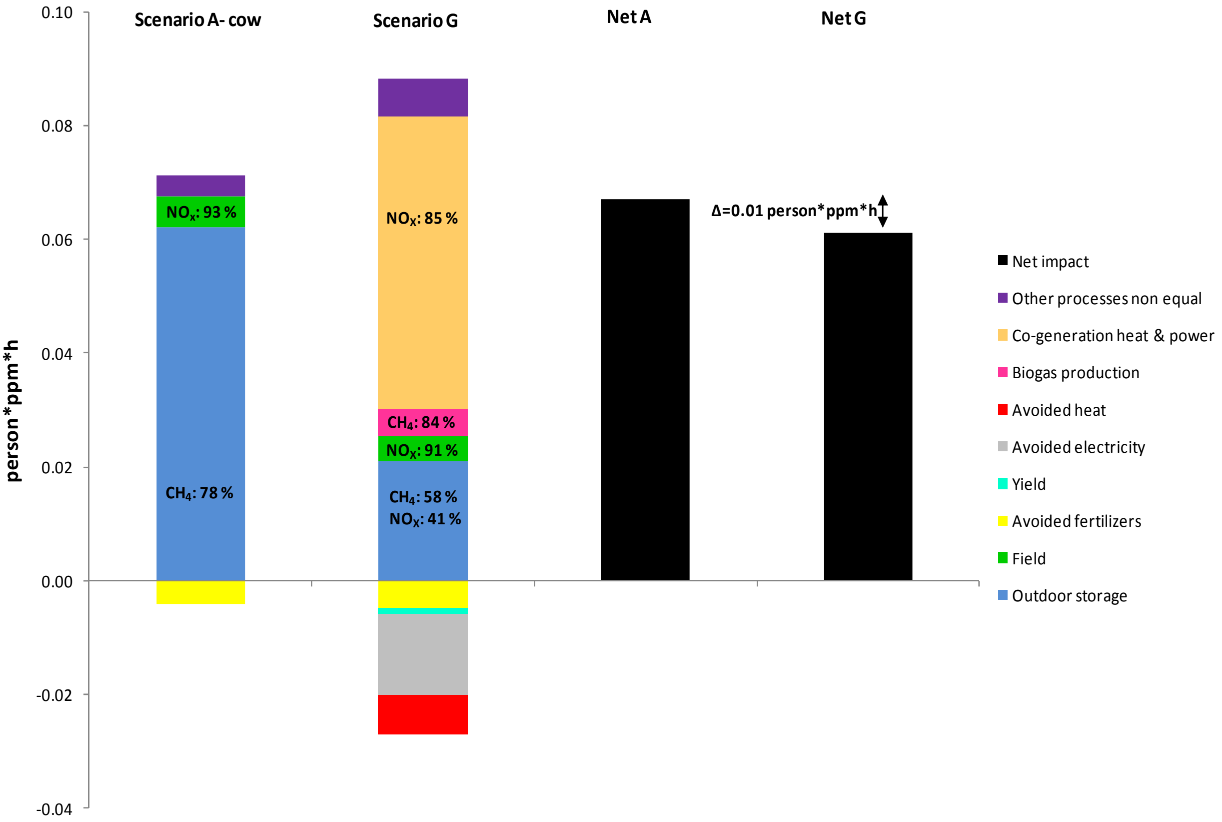
Overall, when the “deductions” from the avoided contributions to photochemical ozone formation are accounted for, the difference between managing the slurry as described in Scenario G as compared to the reference slurry management is 0.01 pers*ppm*h (figure 5.7). However, when taking the uncertainties into account, this difference is not significant (figure 5.10.A).

The major results as regarding photochemical ozone formation potential can be summarised as:

- There are no significant benefits in managing the slurry as in Scenario G for the impact category photochemical ozone formation.
- For both scenarios, in-house storage is a hot spot process as regarding ozone formation impact, essentially because of CH_4 emissions.
- For Scenario G, the emissions of NO_x during the combustion of biogas for co-generation of heat and power also contribute significantly to ozone formation potential.
- Contributions to ozone formation during slurry storage are much lower in Scenario G as compared to Scenario A due to the positive effect of slurry separation and digestion on CH_4 emission potential.

This information is summarised in figure 5.7. This figure presents the contributions to photochemical ozone formation of Scenarios A and G only for the processes that are not equal between A and G (i.e. in-house storage and avoided N fertiliser are not included). All processes are presented; the category labelled “other processes non equal” represents the aggregation of all processes not presented in the legend.

Figure 5.7.
Comparison of Scenario G vs Scenario A for photochemical ozone formation, for processes differing between A and G only. Soil JB3, 10 years values.



5.2.7 Respiratory inorganics (small particles)

This impact category involves, for both scenarios, 2 main contributing processes. These are:

- In-house storage of slurry, representing, for both scenarios, about 35 % of the total positive contributions to respiratory inorganics from the reference scenario.
- Field processes
    - Scenario A: This represents about 49 % of the total positive contributions to respiratory inorganics from the reference scenario.
    - Scenario G: This represents about 45 % of the total positive contributions to respiratory inorganics from the reference scenario (11% liquid fraction; 5% degassed fibre fraction and 29 % degassed liquid fraction).

For Scenario G, another important contributor is the co-generation of heat and power from biogas, representing 19 % of the total positive contributions to respiratory inorganics from the reference scenario.

For in-house storage, the main contributor is NH_3 emissions, representing about 93 % of the contribution to respiratory inorganics for this process. This, as discussed in section 5.2.3, emphasises the importance of reducing NH_3 from animal buildings.

For field processes, in Scenario G, NH_3 is also the main contributor to respiratory inorganics, accounting for 95 % of the contributions for this process. The contribution from the degassed liquid fraction is higher than the other two organic fertilisers for the same reasons as explained in section 4.2.3 (acidification).

Co-generation of heat and power from the biogas has for main contributor to “respiratory inorganics” NO_x, which are emitted during the combustion of the biogas in the biogas engine (NO_x represents 96 % of the total contributions to respiratory inorganics for this process).

Avoiding inorganic fertilisers to be produced (N, but to a smaller extent P and K) also contributes to reduce the contribution to respiratory organics, in similar magnitude for both scenarios. However, the avoided production of marginal heat and electricity in Scenario G contributes to “extra” avoidance of contribution to “respiratory inorganics”. So does the avoided wheat production induced by increased yield, but this represents a rather small avoided contribution.

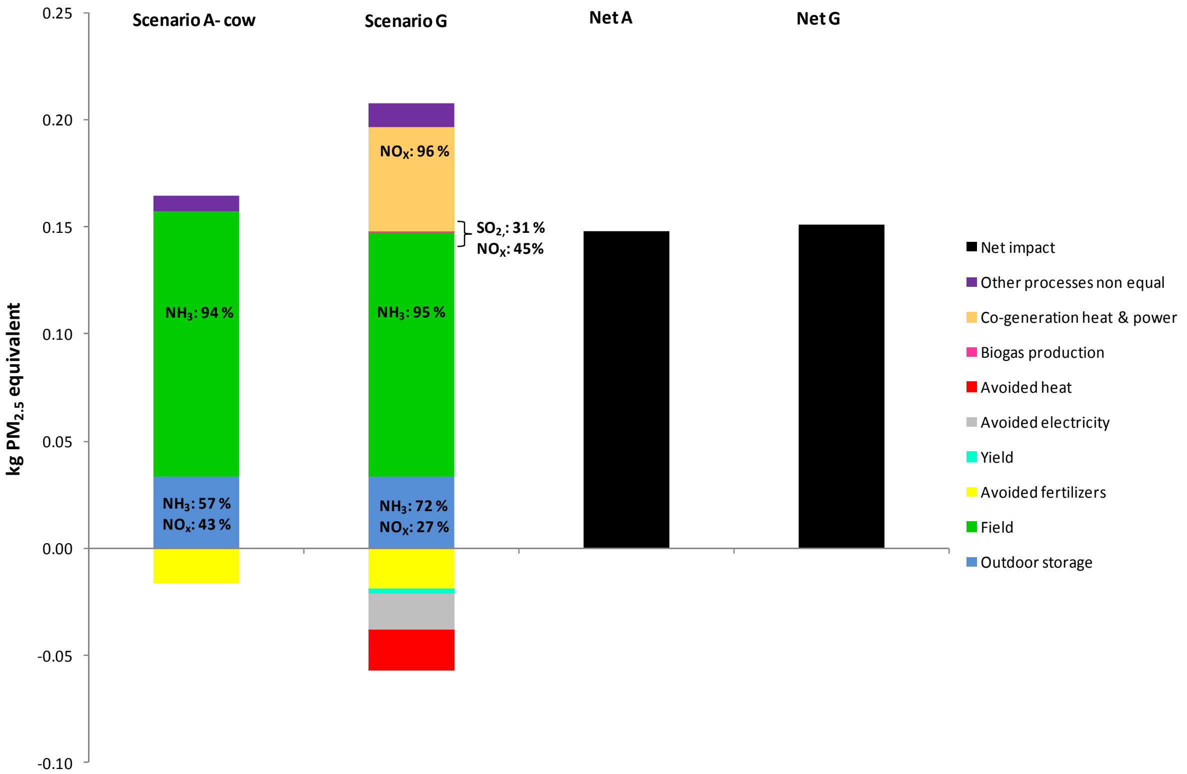
Overall, when the “deductions” from the avoided contributions to “respiratory inorganics” are accounted for, there are no significant benefits to manage the slurry as described in Scenario G in comparison the the reference slurry management. This is illustrated in figure 5.8 and figure 5.10.A.

The major results as regarding respiratory inorganics potential can be summarised as:

- There are no significant benefits obtained with Scenario G as compared to the reference scenario for the impact category “respiratory inorganics”.
- Two main processes contribute to “respiratory inorganics”: in-house storage of slurry and field processes, for both Scenario G and the reference scenario. For these two processes, the main responsible substance to “respiratory inorganics” is NH_3.
- Co-generation of heat and power for Scenario G also contributes significantly to “respiratory inorganics”, and in this case it is mainly due to NO_X emissions during biogas combustion in the engine.

This information is summarised in figure 5.8. This figure presents the contribution to “respiratory inorganics” of Scenarios A and G only for the processes that are not equal between A and G (i.e. in-house storage and avoided N fertiliser are not included). All processes are presented; the category labelled “other processes non equal” represents the aggregation of all processes not presented in the legend.

Figure 5.8.
Comparison of Scenario G vs Scenario A for respiratory inorganics, for processes differing between A and G only. Soil JB3, 10 years values.



5.2.8 Non-renewable energy resources

This category involves, for both Scenario G and Scenario A, the following common hot spot:

- Transport process
    - Scenario A: 41 % of the total positive contributions to “use of non-renewable energy resources” from the reference scenario. The main contributing substance for this process is crude oil (58 %).
    - Scenario G: 73 % of the total positive contributions to “use of non-renewable energy resources” from the reference scenario. The main contributing substance for this process is crude oil (69 %).
- Use of energy (mostly electricity but also heat). This is translated by:
    - Process “outdoor storage-electricity” for Scenario A;
    - Process “Biogas production” for Scenario G;

This impact category is the only category where transport is significant and reflects the use of diesel to fuel the tractors and to transport the slurry by trucks between the farm and the biogas plant.

In the case of Scenario A, “field process” contributes to the use of non-renewable energy in about the same magnitude as “outdoor storage-electricity”. In the case of field process, this reflects the use of diesel for spreading operations.

The process requiring energy inputs appeared as hot spots for the non-renewable energy resources. For Scenario G, the production of biogas can be highlighted, representing 110 % of the total positive contributions to “use of non-renewable energy resources” from the reference scenario. The main contributors to the “non-renewable energy resources” impact from this process are hard coal (79 %) and natural gas (14 %). This is because of the consumption of electricity and heat for running the anaerobic digestion process (see section G.15.3, Annex G). The electricity consumption for producing biogas was estimated as 5% of the net energy production from the biogas. As discussed in section G.15.3 of Annex G, this may however be higher and represent 10 % of the net energy production. In such a case, this would simply double to amount of energy used, and increase the contribution of the biogas production process to the “non-renewable energy resources” category accordingly. The heat consumption for the process was calculated based on heating the biomass mixture from 8°C to the process temperature of 37°C (a temperature difference of 29°C). Reducing this temperature difference through heat exchangers would contribute to slightly attenuate the contribution from the biogas process to the present impact category, but this is likely to represent a rather small contribution overall, as the negative contributions for this impact category are much larger than the positive contributions.

This means, in the case of Scenario G, that producing biogas allow to avoid the consumption of non-renewable energy much more than it contribute to it. This is particularly due to the consumption and production of marginal electricity that is avoided, but also to avoided marginal heat and fertilisers (particularly N). Avoiding fertilisers to be produced and used also has a positive effect on the non-renewable energy consumption for Scenario A, and such benefits are in the same order of magnitude for both Scenarios, except for P where a little more non-renewable energy is saved in the case of Scenario G, as this scenario involve no excess P.

In the case of Scenario G, the avoided wheat production induced by higher yield also contributes to avoided contributions to “non-renewable energy” impact category, but this is rather small as compared to the contributions from the avoided fertilisers and avoided energy.

For this impact category, all storage process appears rather insignificant contributors, as they all require little or no energy input.

Overall, when the “deductions” from the avoided contributions to non-renewable energy use are accounted for, managing the slurry as described in Scenario G allows a reduction of 946 MJ of (primary) non-renewable energy use as compared to the reference scenario.

The major results as regarding the use of non-renewable energy resources can be summarised as:

- Managing the slurry as described in Scenario G allow significant reductions of the use of non-renewable energy resources, as compared to the management of slurry as in the reference scenario.
- For Scenario G, the positive contributions to this impact are more than the double of those from Scenario A; on the other hand, the avoided contributions to this impact are approximately 3 times higher for Scenario G than Scenario A, which makes Scenario G overall more environmentally beneficial as regarding this impact category.
- The main contributors to this impact are transport processes as well as processes involving energy input. In both cases, the main contributors

are fossil resources use (crude oil, hard coal and natural gas, among others).

- Avoiding marginal electricity to be produced (through the use of biogas for electricity) contribute significantly to avoid the consumption of non-renewable energy resources. In an important (but smaller) extent, avoiding N fertilisers to be produced as well as marginal heat also contributes to avoid the use of non-renewable energy resources consumption.

5.2.9 Consumption of phosphorus as a resource

This impact category aims to reflect the importance of phosphorus as a limited and valuable resource. Accordingly, any scenario allowing preventing the use of this limited resource can be highlighted. In the case of this study, this category allows to emphasise the benefits of using slurry as an organic source of P rather than using inorganic P from the limited reserves. As Scenario G allows to save more P (because all the slurry P contributes to avoid inorganic P to be produced, the P not being applied in excess as in Scenario A: section A.6.1 of Annex A and G.28.4 of Annex G), it provides more benefits as compared to Scenario A regarding this impact category. The avoided wheat production induced by higher yields in Scenario G also allows a tiny additional contribution in avoiding P resources to be consumed.

Based on this result, it can be concluded that managing slurry as described in Scenario G offers more advantages over Scenario A as regarding the consumption of P (the difference is 0.13 kg P being saved). This is due to a better management of the P in Scenario G, as the P is concentrated in the solid fraction which is applied in a field where P is deficient. Yet, if this P would be applied in excess as in Scenario A, this benefit would be lost, which highlights the importance of using the P-rich fertiliser produced in Scenario G in a field where it is needed.

5.2.10 Carbon stored in soil

Through Scenario G, a certain amount of C ends up to be stored in soils, which means this C is not emitted as CO_2. This is through the C of the different slurry fractions that is applied to field and not emitted as CO_2.

For the reference scenario, a total of 6.95 kg C per 1000 kg cow slurry ex-animal is stored in soils, corresponding to 25.5 kg CO_2 not emitted per functional unit. This is when considering a horizon of 10 years for C. With the 100 years values, more CO_2 is emitted and consequently less C is stored per functional unit (1.98 kg), resulting to 7.3 kg CO_2 not emitted per 1000 kg cow slurry ex-animal. These values are presented in table 4.2 of Wesnæs et al. (2009).

For Scenario G, less C is added to field per functional unit but also less CO_2 is emitted in the field (as this CO_2 has been emitted already during the combustion of biogas). As a result, the amount of C sequestrated in the soil per functional unit (6.09 kg C considering 10 years values; 1.69 kg C considering 100 years values) is similar to the amount of C sequestrated for the reference scenario. In terms of CO_2 avoided, this corresponds to 22.3 kg CO_2 (10 years values) and 6.2 kg CO_2 (100 years values) per 1000 kg cow slurry ex-animal.

5.2.11 Polymer

This scenario involves the use of cationic polyacrylamide (PAM) as a polymer during the separation (0.60 kg cationic PAM per 1000 kg slurry input in the separation process). This represents 0.28 kg cationic PAM per functional unit. The impact of the polymer fabrication was considered in the assessment, but the fate of this polymer in the environment could not be assessed due to a lack of data.

As explained in section 4.2.11, evidences from the literature suggest that the use of cationic PAM may represent an important concern in the environment. This could not be reflected in this life cycle assessment. Given the importance of the potential risk associated with the cationic PAM fate in the environment, it is suggested to investigate this aspect more deeply before implementing any large scale slurry management projects involving the use of cationic PAM.

5.3 Uncertainties

The uncertainties on the compared results have been estimated by analysing the most important factors that are ***changed***, when comparing scenario G with the reference scenario A. It means that the uncertainties for each scenario is not analysed as such, but only the emissions that are important for the ***differences***. The uncertainties on the comparisons are based on estimates of the uncertainties on those emissions that are most important for the changes.

The uncertainties are related to the total positive contribution from the reference scenario A (i.e. the total that is set to 100% in figures 5.9 and 5.10 as “index”).

The values of the uncertainty ranges are shown in table 5.5.

5.4 Synthesis of the results for all impact categories assessed

Table 5.5 compares the overall characterised results of Scenario A versus Scenario G, for all impacts categories (including carbon stored in soils). It also presents the uncertainty ranges for all impact category results.

Figures 5.9.A and 5.9.B illustrate the results presented in table 5.5, and give an impression of the uncertainty. The difference between these two figures is the axis, which has a greater range in the case of figure 5.9.B in order to capture the whole impacts of non-renewable energy consumption. Figures 5.10.A and 5.10.B present only the net differences between Scenario A and G, including the uncertainties.

Table 5.5.
Comparison of the impacts from Scenario A (reference) versus Scenario G (biogas from raw cow slurry + fibre fraction from chemical-mechanical separation). The number of digits is *not* an expression of the uncertainty.

Impact category	Scenario A - dairy cow	Scenario G	Difference, i.e. Biogas scenario G minus Reference scenario A	Conclusion
Global warming (during 10 years) [kg CO_2 eq.]				
Positive contributions:	+ 326 kg	+ 302 kg	-107 [-159 to -82] kg CO_2 eq.	25-49% reduction of positive contributions from scenario A
Negative contributions:	- 40 kg	- 123 kg		
Net:	= 286 kg	= 179 kg		
Global warming (during 100 years) [kg CO_2 eq.]				
Positive contributions:	+ 355 kg	+ 331 kg	-150 [-224 to -116] kg CO_2 eq.	33-63% reduction of positive contributions from scenario A
Negative contributions:	- 51 kg	- 136 kg		
Net:	= 304 kg	= 195 kg		
Acidification [m^2 UES, i.e. area of unprotected ecosystem]				
Positive contributions:	+ 43.3 m^2	+ 45.9 m^2	-2.4 [-10 to +2] m^2 UES	No significant difference due to uncertainties
Negative contributions:	-5.9 m^2	-10.9 m^2		
Net:	= 37.3 m^2	= 35.0 m^2		
N-eutrophication (aquatic) (during 10 years) [kg N - amount reaching aquatic recipients]				
Positive contributions:	+ 1.55 kg	+ 1.58 kg	-0.04 [-0.09 to +0.004] kg N	No significant difference due to uncertainties
Negative contributions:	- 1.00 kg	- 1.07 kg		
Net:	= 0.55 kg	= 0.51 kg		
N-eutrophication (aquatic) (during 100 years) [kg N - amount reaching aquatic recipients]				
Positive contributions:	+ 1.79 kg	+ 1.85 kg	-0.15 [-0.32 to +0.015] kg N	No significant difference due to uncertainties
Negative contributions:	- 1.11 kg	- 1.21 kg		
Net:	= 0.68 kg	= 0.64 kg		
P-eutrophication (aquatic) [kg P - amount reaching aquatic recipients]				
Positive contributions:	+ 0.0063 kg	+ 0.0063 kg	-0.0009 [-0.0005 to -0.0019] kg P	8-30% reduction of positive contributions from scenario A
Negative contributions:	- 0.0089 kg	- 0.0099 kg		
Net:	= -0.0026	= -0.0035		
Photochemical ozone formation [person.ppm.hr - see section 3.4.7]				
Positive contributions:	+ 0.16 p.p.h	+ 0.18 p.p.h	-0.006 [-0.023 to +0.011] p.p.h	No significant difference due to uncertainties
Negative contributions:	-0.02 p.p.h	-0.04 p.p.h		
Net:	= 0.14 p.p.h	= 0.14 p.p.h		
Respiratory Inorganics [kg PM2.5 eq, i.e. kg equivalents of 2.5 µm size particles]				
Positive contributions:	+ 0.25 kg	+ 0.29 kg	-0.003 [-0.030 to +0.0.028] kg PM2.5	No significant difference due to uncertainties
Negative contributions:	- 0.05 kg	- 0.09 kg		
Net:	= 0.20 kg	= 0.20 kg		
Non-renewable energy [MJ primary energy]				
Positive contributions:	+ 131 MJ	+ 250 MJ	-946 [-1230 to -662] MJ	500-930% reduction of positive contributions from scenario A
Negative contributions:	-410 MJ	-1475 MJ		
Net:	= -279 MJ	= -1225 MJ		
Phosphorus Resources [kg P]				
Positive contributions:	+ 0 kg	+ 0 kg	-0.13 [-0.26 to -0.0.066) kg P	A significantly larger amount of P resources saved in scenario G
Negative contributions:	- 1.38 kg	- 1.51 kg		
Net:	= -1.38 kg	= -1.51 kg		
Carbon stored in soil during 10 years [kg C] **and corresponding amount of CO_2-eq**				
C added with slurry:	+ 47.2 kg C	+33.1 kg C	-0.86 [-2.9 to +1.2] kg C -0.32 [-10.8 to +4.5] kg CO2	No significant difference due to uncertainties
C lost as CO2:	- 40.2 kg C	- 27.0 kg C		
C stored in soil:	= 7.0 kg C	= 6.1 kg C		
Net CO2:	= 25.5 kg CO2	= 22.3 kg CO2		
Carbon stored in soil during 100 years [kg C] **and corresponding amount of CO_2-eq**				
C added with slurry:	+ 47.2 kg C	+ 33.1 kg C	-0.3 [-0.9 to +0.3] kg C -0.1.1 [-3.4 to +1.1] kg CO_2	No significant difference due to uncertainties
C lost as CO2:	- 45.2 kg C	- 31.4 kg C		
C stored in soil:	= 2.0 kg C	= 1.7 kg C		
Net CO2:	= 7.3 kg CO2	= 6.2 kg CO2		

Note: All numbers are all rounded and accordingly, if the reader calculates the difference, it might vary slightly from the numbers shown in the table.

Figure 5.9.A
Comparison of the environmental impacts from Scenario A (reference) versus Scenario G (biogas from raw cow slurry + fibre fraction from mechanical-chemical separation). Axis ranging from -180 to 120.

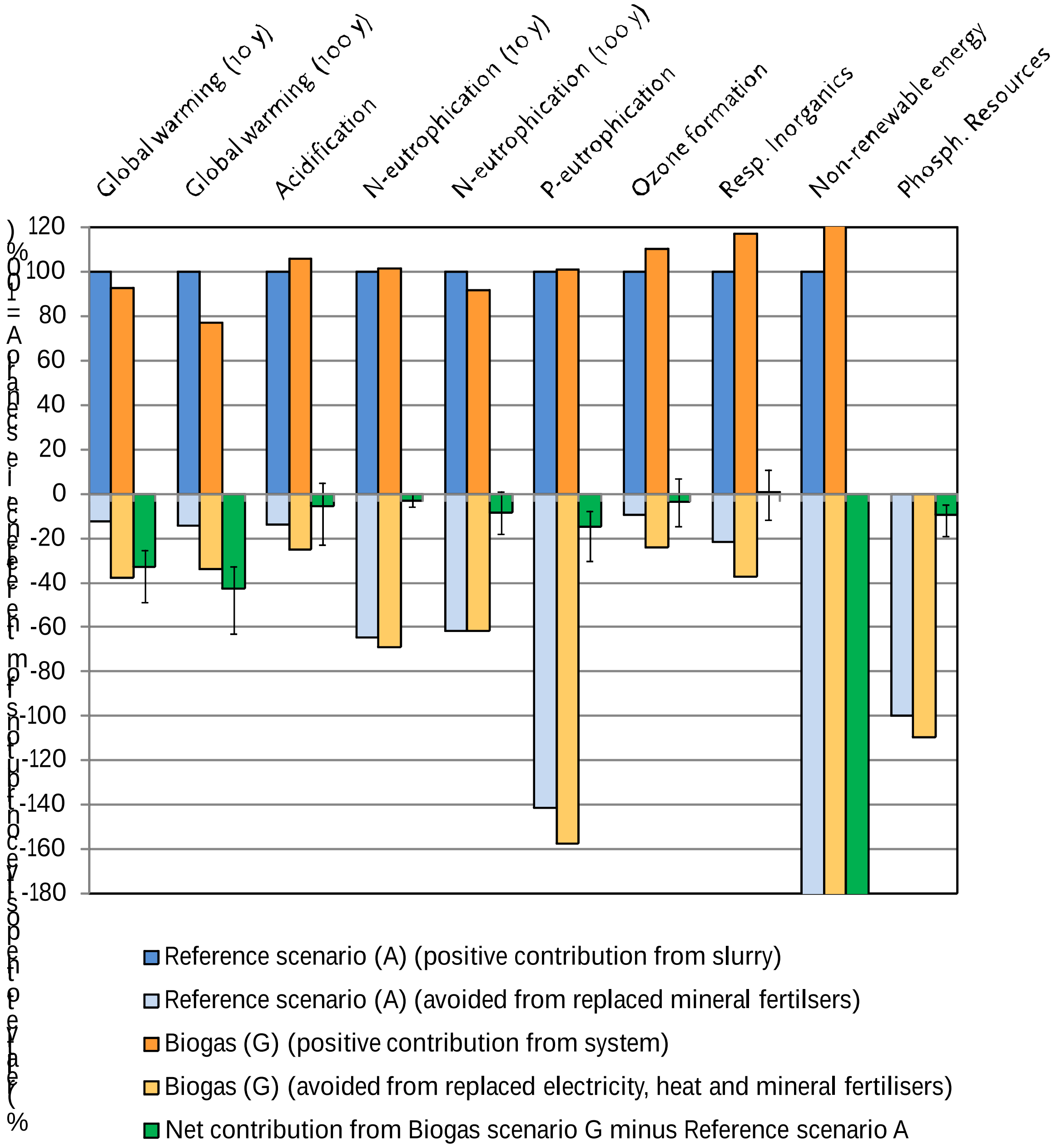


Figure 5.9.B
Comparison of the environmental impacts from Scenario A (reference) versus Scenario G (biogas from raw cow slurry + fibre fraction from mechanical-chemical separation). Axis ranging from -1200 to 200.

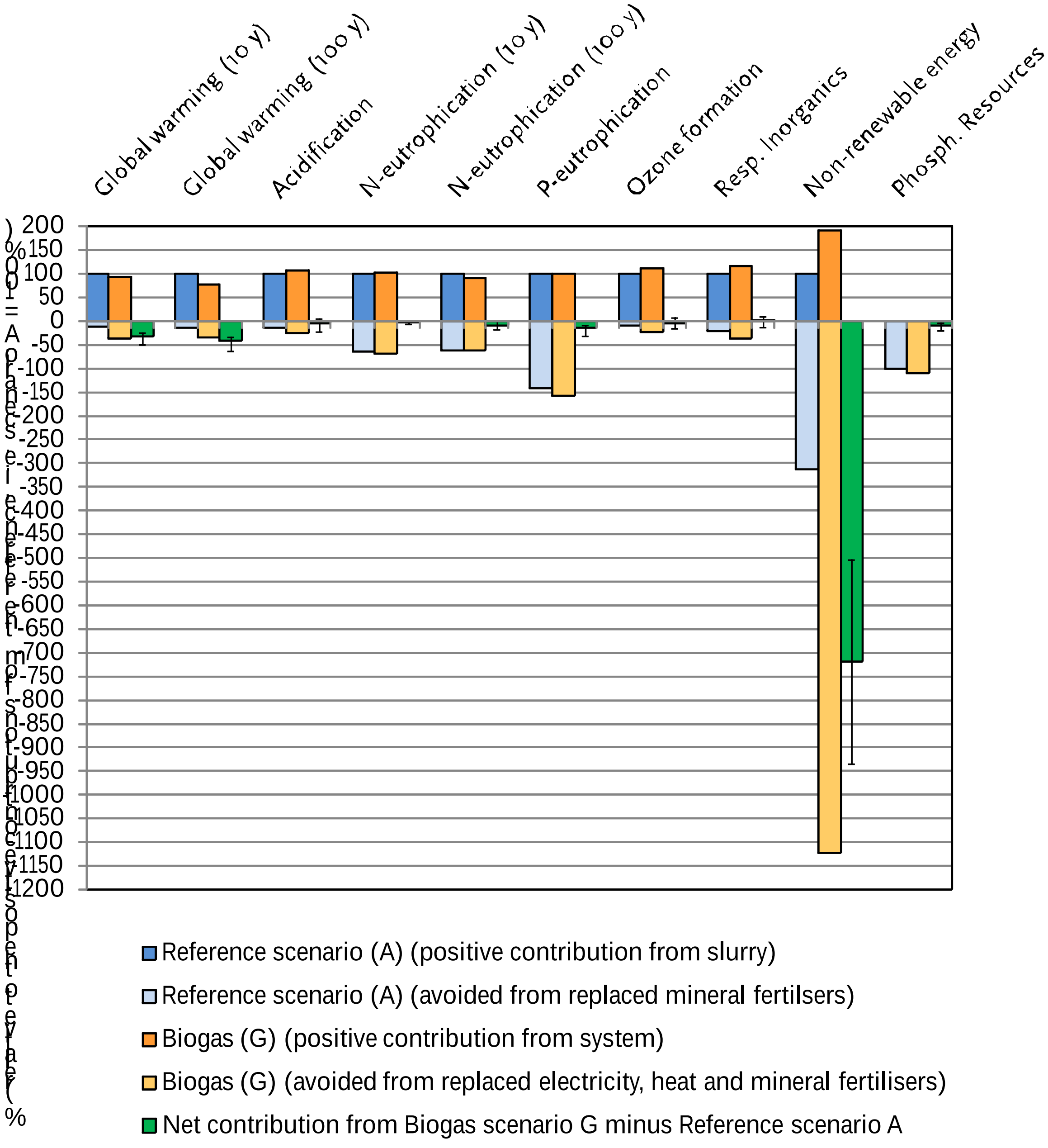


Figure 5.10.A
Comparison of the environmental impacts from Scenario A (reference) versus Scenario G (biogas from raw cow slurry + fibre fraction from mechanical-chemical separation). Net difference only. Axis ranging from -100 to 100.

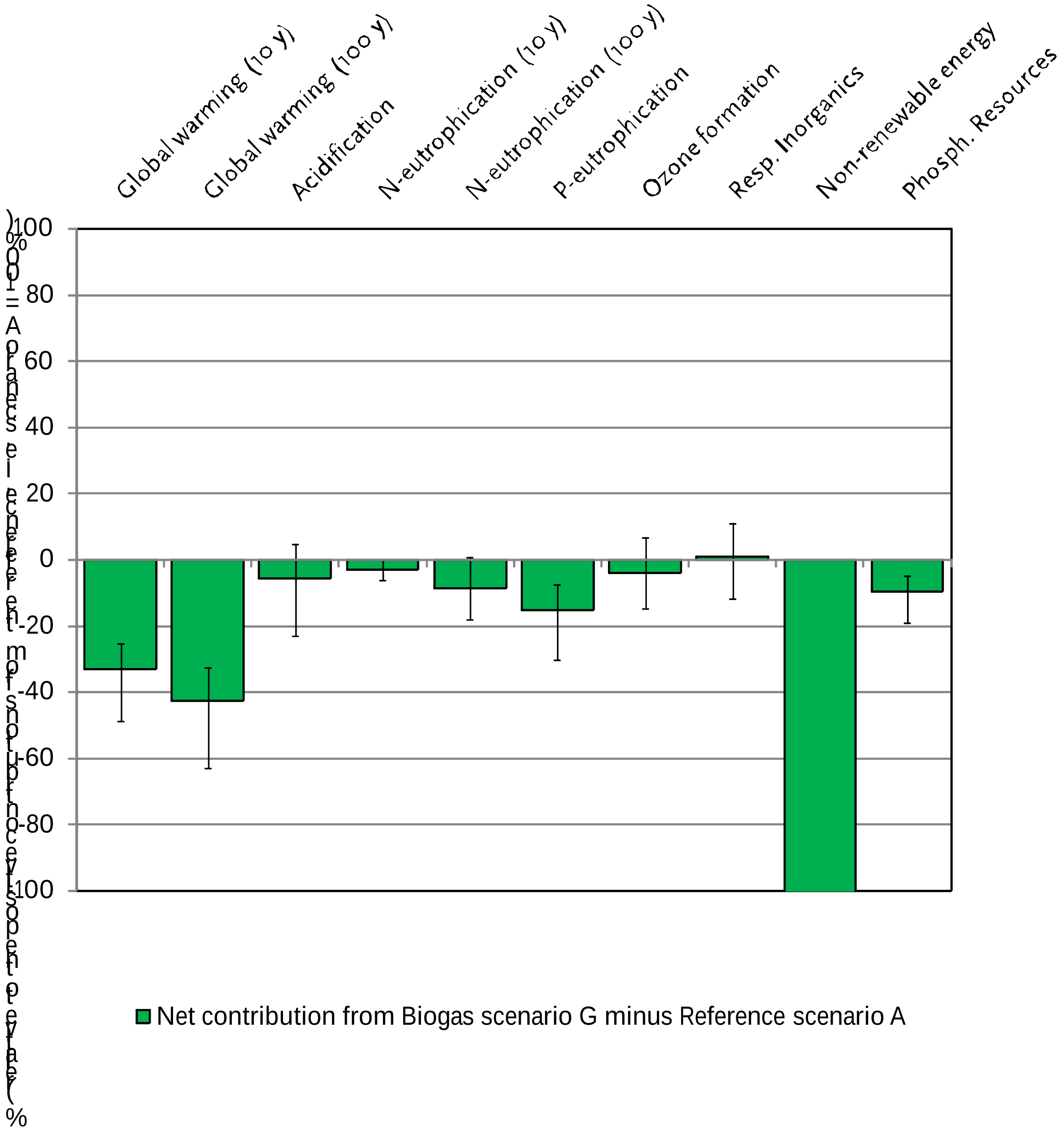
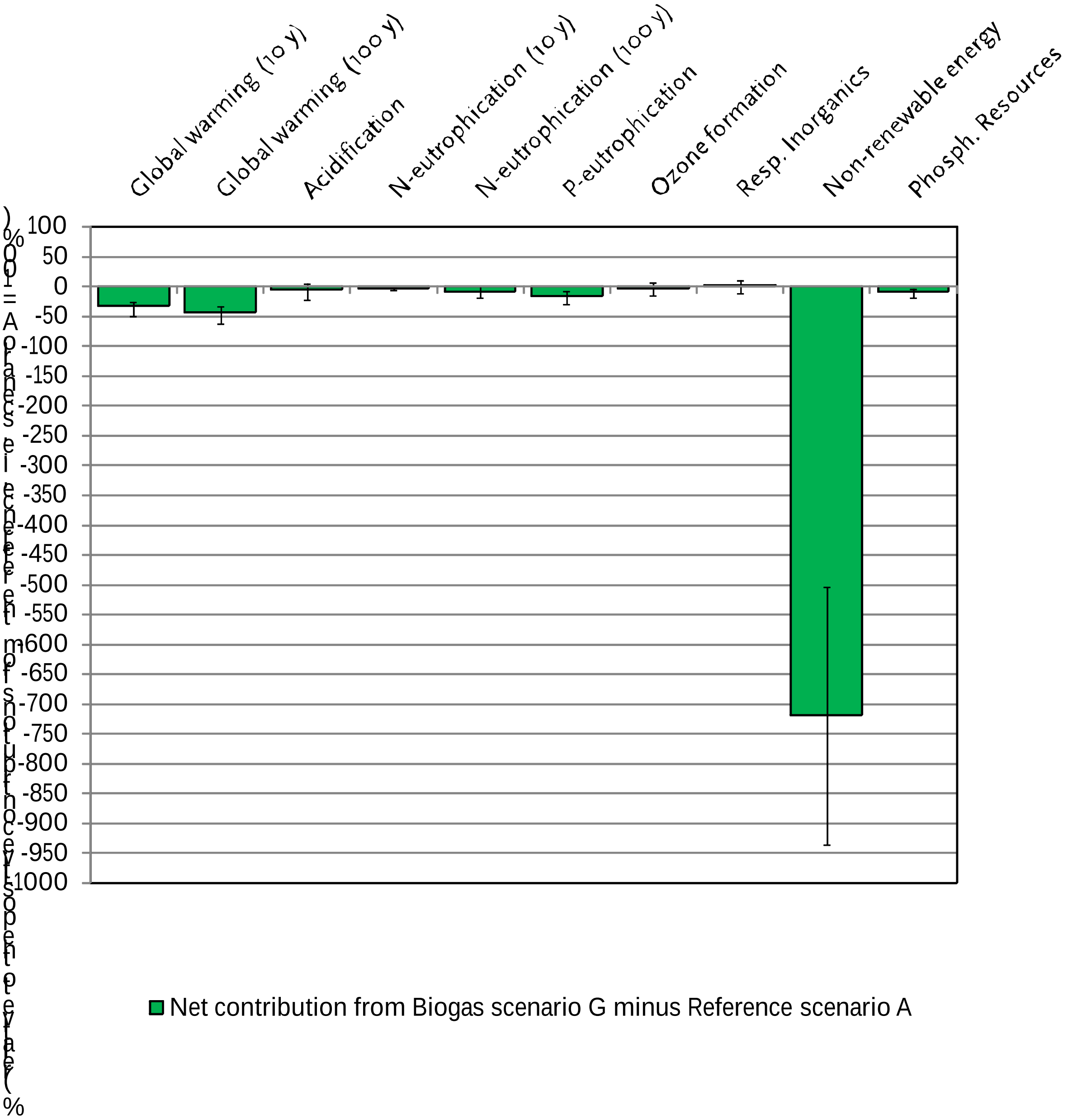


Figure 5.10.B
Comparison of the environmental impacts from Scenario A (reference) versus Scenario G (biogas from raw cow slurry + fibre fraction from mechanical-chemical separation). Net difference only. Axis ranging from -1000 to 200.



6 Biogas production from raw pig slurry and fibre fraction from mechanical screw press separation (Scenario H) – results and interpretation

This section presents the results and the interpretation from the life cycle assessment carried out for "Scenario H", described below. The results from "Scenario H" are compared to those of the reference scenario for fattening pig slurry management, i.e. "Scenario A". The life cycle assessment is performed in order to answer the research question: ***"What are the environmental benefits and disadvantages of using the fibre fraction from Samson Bimatechs mechanical separation of pig slurry (see Annex C) for biogas production compared to the reference scenario for pig slurry management?".***

This scenario does ***not*** rely on "best available technologies" or "best possible practices" as it was the case for Scenarios F and G.

The detailed description of this scenario, including all mass balances, assumptions and calculations, is presented in Annex H. All life cycle inventory data used for the results presented in this section can therefore be found in Annex H.

The environmental impacts and conclusions in this section build, among others, on data and information delivered by the producer of the technology, Samson Bimatech, and on data measured for Samson Bimatech (laboratory measurements of the slurry composition), combined with data for biogas production based on information from Xergi. The conclusions made in this section rely on this information, and the authors of this study have not had the possibility of verifying these data.

6.1 System description

The system constituting Scenario H, as described in section 2.2.4, consists to produce biogas from a mixture of raw slurry and fibre fraction obtained from a mechanical screw press separation (Samsom Bimatech process), both from fattening pigs. This scenario is highly similar to Scenario F, but some major differences can be highlighted.

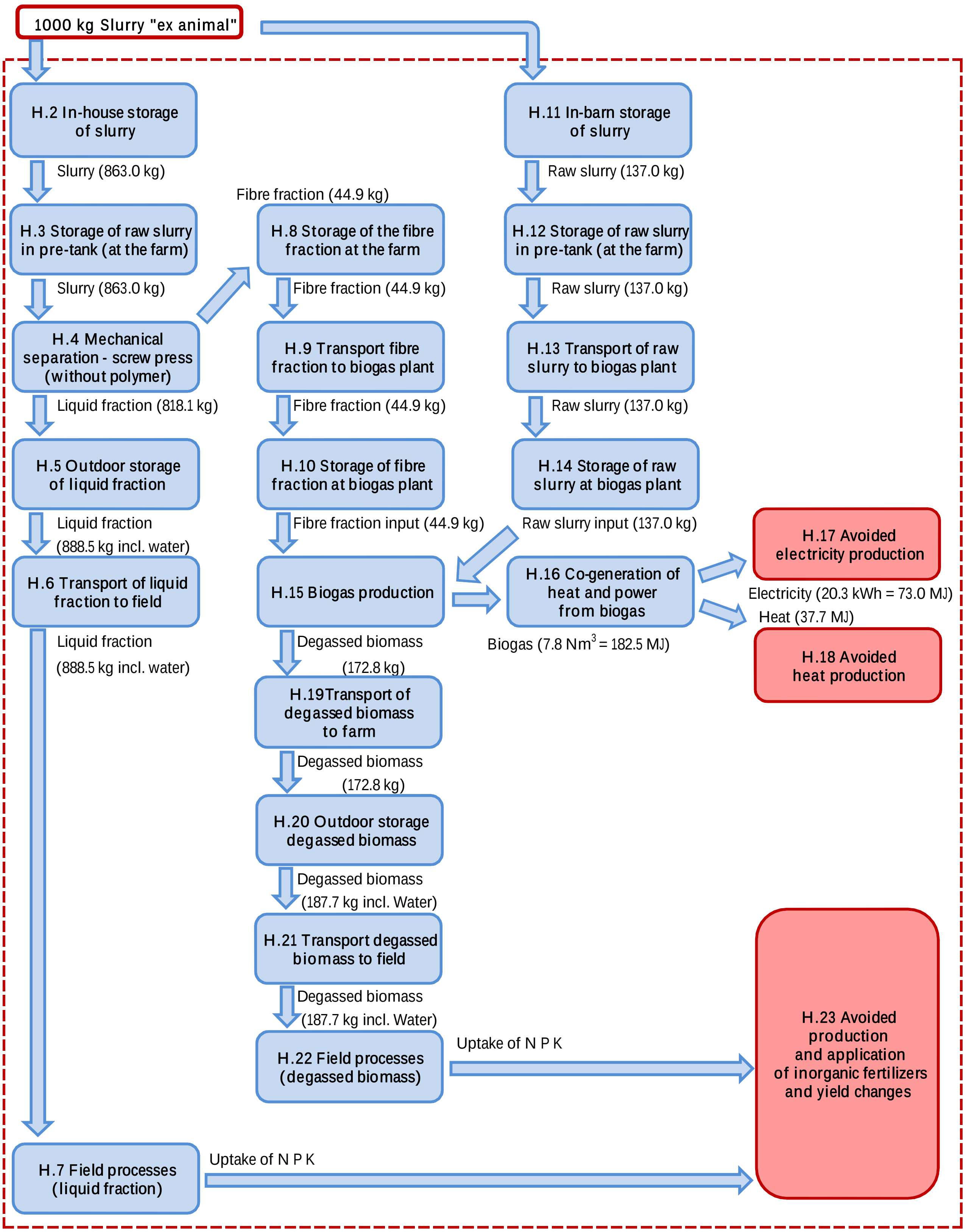
The main differences between Scenario H and Scenario F are:

- The separation technology of Scenario H is based on a mechanical screw press separation (the Samson Bimatech separation technology). In Scenario H, polymer is not added to the separation (polymer is added for the separation in Scenario F).
- No separation of the degassed biomass mixture resulting from the anaerobic digestion is performed after the biogas plant. This involves

that the subsequent storage and field processes concern the degassed biomass only.

A flow diagram for “Scenario H” is shown in figure 6.1. The process numbers in figure 6.1 follows the numbers of the sections in Annex H.

Figure 6.1.
Process flow diagram for “scenario H” – Biogas production from raw pig slurry and fibre fraction from mechanical screw press separation. The process numbers follows the numbers of the sections in annex H.



6.2 Results of the Impact Assessment

6.2.1 Overall results of the comparison

Table 6.1 presents the overall environmental impacts from “Scenario H” (biogas from raw pig slurry and fibre fraction from mechanical separation), and compare them to the environmental impacts from the reference scenario for pig slurry (described in section 3). Figures 6.2 A and 6.2.B illustrate the results presented in table 6.1. Figures 6.2 A and 6.2.B are identical except for the minimum and maximum at the axis. In the case of figure 6.2.B, the minimum and maximum were adjusted in order to present fully the consumption of non-renewable energy impact category. As in previous sections, results are presented for soil JB3 only (sandy soil).

As explained in section 4.2.1, the results presented are “characterised” results and are expressed, for each impact categories, relative to the result of the reference scenario. The positive values are the contributions to the environmental impacts and resource consumptions by the slurry management scenarios. The negative values are “avoided environmental impacts”.

Results presented in table 6.1 should be interpreted with care in the light of the assumptions and data that were used to obtain them, i.e. the life cycle inventory (LCI) data presented in Annex H. An attempt to discuss these results based on this focus, impact category per impact category, is presented in sections 6.2.2 to 6.2.10.

Table 6.1.

Scenario H vs A: Contribution of the different processes to each environmental impact categories selected. Results, for each impact category, are expressed in % of the total positive contributions from the reference scenario (considering the 10 years values, when this applies). Soil JB3 (sandy)[1]

Impact Categories	GW (10 y)	GW (100 y)	Acidification	Eutrophication (N) (10 y)	Eutrophication (N) (100 y)	Eutrophication (P)	Ozone formation	Respiratory inorganics	Non-renewable energy	Phosphorus resources
SCENARIO A - pig										
A.2 In-house storage	31.7	31.7	60.0	16.3	16.3	0.0	56.2	56.2	0.0	0.0
A.3 Outdoor storage - elect	1.4	1.4	0.3	0.0[a]	0.0[a]	0.0[a]	0.5	0.4	37.0	0.0[a]
A.3 Outdoor storage	21.4	21.4	8.0	2.4	2.4	0.0	38.7	10.4	0.0	0.0
A.4 Transport to field	1.2	1.2	0.6	0.2	0.2	1.1	1.8	2.5	36.8	0.0[a]
A.5 Field processes	44.3	51.2	31.1	81.1	89.1	98.8	2.8	30.5	26.2	0.0[a]
A.6 N fertiliser	-10.6	-14.3	-7.9	-61.1	-67.7	-1.8	-5.8	-12.1	-170.1	0.0[a]
A.6 P fertiliser	-1.5	-1.5	-2.8	-0.1	-0.1	-121.8	-1.3	-4.5	-51.2	-99.9
A.6 K fertiliser	-0.6	-0.6	-0.2	0.0[a]	0.0[a]	-0.5	-0.6	-0.7	-22.2	-0.1
Sum of positive contributions	***100***	***107***	***100***	***100***	***108***	***100***	***100***	***100***	***100***	***0.0*[a]**
Sum of negative contributions	***-13***	***-16***	***-11***	***-61***	***-68***	***-124***	***-8***	***-17***	***-244***	***-100***
SCENARIO H										
H.2 + H.11 In-house storage	31.7	31.7	60.0	16.3	16.3	0.0	56.2	56.2	0.0	0.0
H.3 + H.12 Pre-tank storage	0.5	0.5	0.1	0.0[a]	0.0[a]	0.0[a]	0.2	0.1	12.6	0.0[a]
H.4 Separation – elect & equipment	0.2	0.2	0.0[a]	0.0[a]	0.0[a]	0.1	0.1	0.1	6.4	0.0[a]
H.5 Outdoor storage liquid fraction	13.6	13.6	6.5	1.9	1.9	0.0[a]	22.5	8.5	8.8	0.0[a]
Transport (H.6, H.9, H.13, H.19, H.21)	1.4	1.4	0.7	0.2	0.2	1.3	2.1	2.9	43.8	0.0[a]
H.7 Field processes (liquid fraction)	27.6	33.3	13.4	64.3	71.2	77.6	2.3	13.9	21.5	0.0[a]
H.8 Storage fibre fraction on-farm	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.0[a]
H.10 Storage fibre fraction at biogas plant	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
H.14 Storage raw slurry biogas plant	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
H.15 Biogas production	0.6	0.6	0.1	0.0[a]	0.0[a]	0.0[a]	0.7	0.1	7.6	0.0[a]
H.16 Co-generation heat and power	5.9	5.9	1.9	0.6	0.6	0.0[a]	7.8	4.5	1.2	0.0[a]
H.17 Avoided electricity production	-5.8	-5.8	-1.1	-0.1	-0.1	-0.2	-2.2	-1.6	-150.3	0.0[a]
H.18 Avoided heat production	-1.7	-1.7	-1.3	-0.1	-0.1	-0.2	-1.0	-1.7	-32.4	0.0[a]
H.20 Outdoor storage (degassed biomass)	2.7	2.7	1.4	0.4	0.4	0.0[a]	4.5	1.7	3.7	0.0[a]
H.22 Field processes (degassed biomass)	10.9	12.9	6.4	14.7	18.2	21.2	0.5	6.2	4.5	0.0[a]
H.23 N fertiliser – production & application on JB3	-10.6	-14.3	-7.9	-61.1	-67.7	-1.8	-5.8	-12.1	-170.1	0.0[a]
H.23 P fertiliser – production & application on JB3	-1.5	-1.5	-2.8	-0.1	-0.1	-121.8	-1.3	-4.5	-51.2	-99.9
H.23 K fertiliser – production & application on JB3	-0.6	-0.6	-0.2	0.0[a]	0.0[a]	-0.5	-0.6	-0.7	-22.2	-0.1
H.23 Yield changes	-0.6	-1.5	-0.5	-2.6	-5.6	-1.7	-0.3	-0.6	-6.1	-1.0
Sum of positive contributions	***95***	***103***	***90***	***98***	***109***	***100***	***97***	***94***	***110***	***0.0*[a]**
Sum of negative contributions	***-21***	***-25***	***-14***	***-64***	***-74***	***-126***	***-11***	***-21***	***-432***	***-101***

[1] The number of digits is not an expression of the uncertainty. All numbers are all rounded and accordingly, if the reader calculates the sum or the difference, it might vary slightly from the numbers shown in the table.

[a] This number is not a zero value.

Figure 6.2.A
Overall environmental impacts for the selected impact categories – scenario H vs scenario A. Fattening pig slurry management. Soil type JB3. 10 and 100 years time horizon for global warming and for aquatic eutrophication (N). Axis ranging from -140 to 120.

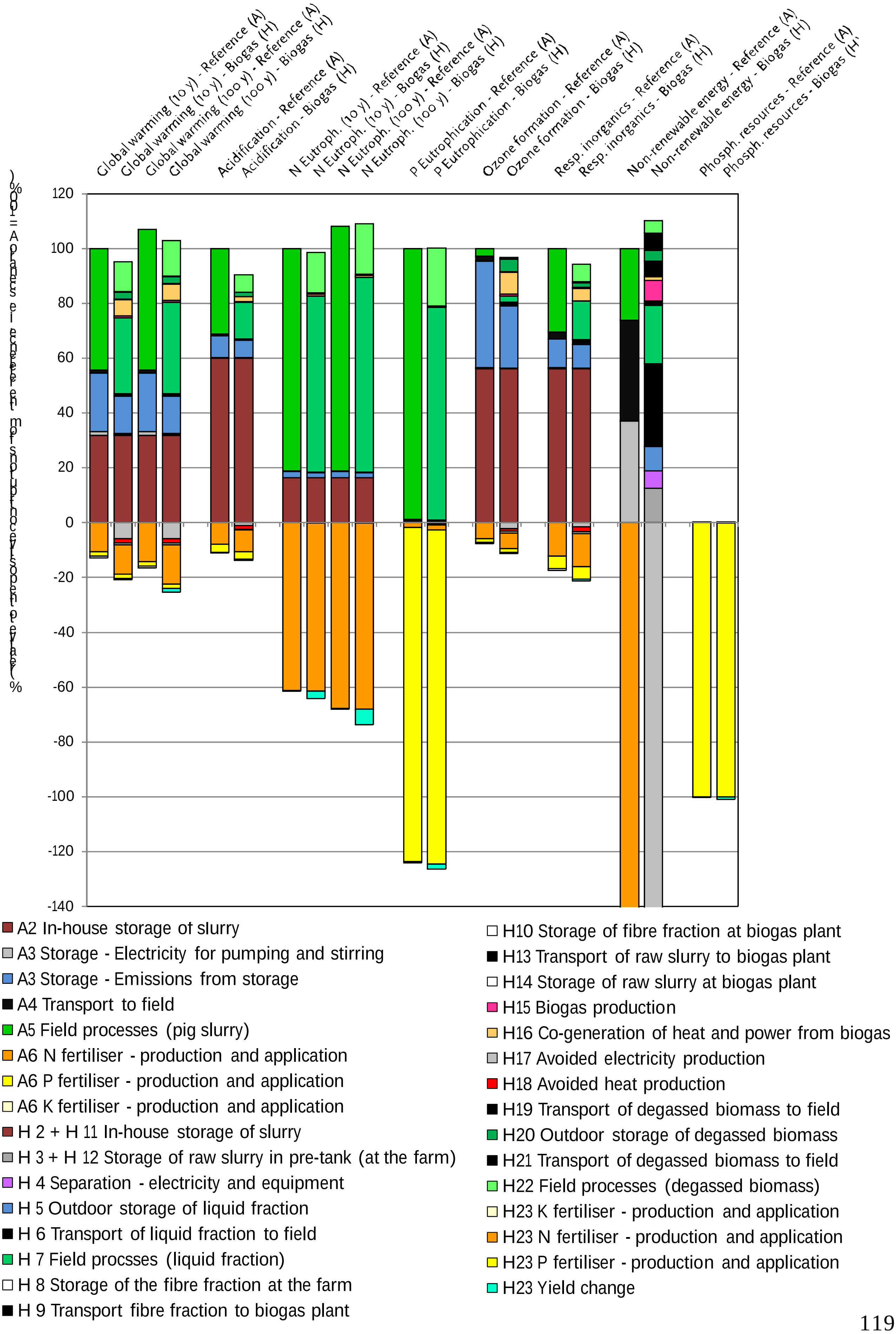
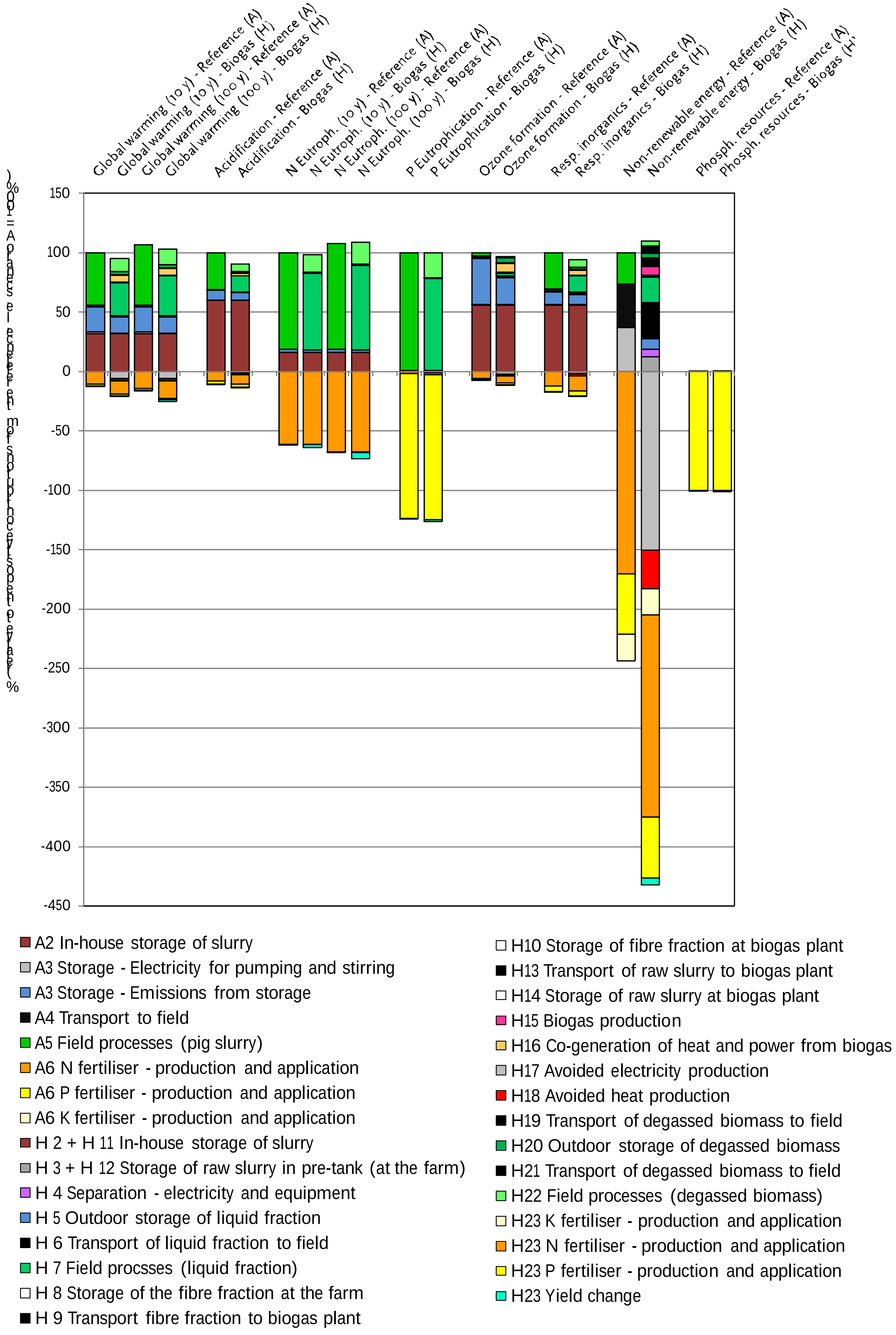


Figure 6.2.B
Overall environmental impacts for the selected impact categories – scenario H vs scenario A. Fattening pig slurry management. 10 and 100 years time horizon for global warming and for aquatic eutrophication (N). Axis ranging from -450 to 150.



In the following sections, the benefits (and shortcomings) of producing biogas as described in Scenario H instead of the reference slurry management are discussed in details for each impact categories.

Sensitivity analyses were performed for some processes, as described in Annex H. The results of these sensitivity analyses are presented in section 8 of this report. However, as all the sensitivity analyses identified concern the same processes as for Scenario F, the sensitivity analyses are performed with the data of Scenario F only.

6.2.2 Global warming

From table 6.1 as well as figure 6.2.A, it can be observed that two main processes contribute to global warming:

- In-house storage (for both Scenario A and H, this process represents 32 % of the total positive contributions to global warming from the reference scenario).
- Field processes.
    - For Scenario A, this represents 44 % of the total positive contributions to global warming from the reference scenario (and 51 % if the 100 years values are considered for C horizon in the field).
    - For Scenario H, this represents 39 % of the total positive contributions to global warming from the reference scenario (and 46 % if the 100 years values are considered for C horizon in the field).

The main contributing substance for in-house storage contribution to global warming is CH_4 (representing, for Scenario H, 84 % of the contribution from this process). The other contributors are N_2O (12%) and CO_2 (4 %). The proportions shown in parenthesis are for a 10-years value as regarding the horizon considered for C in the field. This process is exactly the same for Scenario A, F, H and I. In section 4.2.2, the explanations and discussions about the importance of CH_4 emissions versus the assumptions taken are presented.

The contribution to global warming from field process is less important if the slurry is managed as described in Scenario H than as in the reference scenario. This is mainly due to less biogenic CO_2 emissions from the field in Scenario H (74 kg CO_2 equivalent in Scenario H as compared to 89 kg CO_2 equivalent in Scenario A). The biogenic CO_2 emissions in this case represent the emissions of CO_2 from the applied slurry in the field. Less biogenic CO_2 emissions for Scenario H are due to the anaerobic digestion effect, where an important share of the C was removed from the slurry and used to produce energy. In fact, the emissions of biogenic CO_2 from the liquid fraction (50 kg CO_2 equivalent) are about the double as those from the digested biomass (24 kg CO_2 equivalent). Overall, biogenic CO_2 contribute to 67 % of the contribution to global warming from field processes in Scenario H (considering 10 years values horizon for C in the field). For Scenario A, this is 70 %.

The other important contributing substance to global warming from field processes is N_2O. As explained in section 4.2.2, the emissions of N_2O were estimated based on the IPCC methodology (IPCC, 2006), accordingly, the emissions were estimated as a function of the N content in the applied slurry. As such, the contribution to global warming from the emissions of N_2O of the degassed biomass (6.6 kg CO_2 equivalent) are much lower than from the liquid fraction (26.6 kg CO_2 equivalent) which has a higher N content. However, if the IPCC methodology underestimate N_2O emissions from field as suggested by Crutzen et al. (2008), the global warming from field process could be much more important, as detailed in section 4.2.2.

For both Scenario A and H, outdoor storage appears as the third most important contributing process to global warming. In Scenario A, this process represents 21 % of the total positive contributions to global warming from the reference scenario and the main contributing substance is CH_4 (44.6 kg CO_2 equivalent, representing 73 % of the contributing substances to global warming from this process). In Scenario H, this process represents, when accounting for all fractions to be stored (liquid fraction and degassed biomass), 16 % of the total positive contributions to global warming from the reference scenario. In this case, the main contributing substance is also CH_4, but with 28.5 kg CO_2 equivalent (representing 61 % of the contributing substances to global warming from this process). From this 28.5 kg CO_2 equivalent, 23.5 kg is from the storage of the liquid fraction and 5 kg is from the storage of the degassed biomass. This illustrates the positive effect of digestion for storage of slurry, as most of the VS (whose degradation is the origin for CH_4 emission) were degraded during the anaerobic digestion, leaving a much lower potential for subsequent CH_4 emissions. Methane emissions from the liquid fraction may however be slightly overestimated in this study, as it was assumed that all the VS present in the liquid fraction are easily degradable (see section 4.2.2 of this report and F.5.4 of Annex F). This also applies for N_2O, as described in section F.5.7 of Annex F. Emissions of N_2O actually contribute to 32 % of the contribution to global warming from outdoor storage in Scenario H (i.e. 14.8 kg CO_2 equivalent). Most of it comes from the liquid fraction (12.9 kg CO_2 equivalent).

For Scenario H, the contribution to global warming from co-generation of heat and power does not have an important magnitude as compared to the other biogas scenarios because of the lower amount of biogas produced per functional unit.

Finally, as it can be observed from figure 6.2.A, the contributions to global warming from the use of electricity, the biogas process and the transportation are rather negligible.

Using the slurry as an organic fertiliser allows, for both scenarios, to avoid the same amount of inorganic fertiliser to be produced, and consequently, contribute to avoid the same magnitude of global warming potential to be avoided. However, the biogas production in Scenario H has the additional advantage to avoid heat and electricity to be produced, which allows more global warming potential to be avoided. The avoided wheat production induced by an increased yield in Scenario H does not contribute significantly to avoid global warming potential, as shown in figure 6.2.

Overall, when the “deductions” from the avoided contributions to global warming are accounted for, managing the slurry as described in Scenario H allow a net reduction of 37 kg CO_2 equivalent of the global warming potential as compared to the reference scenario (figure 6.3).

Table 6.2 summarises, for selected processes, the contribution of the main contributing substances to global warming, for both Scenario A and H.

Table 6.2.
Scenario H vs A: Contribution of the main contributing substances to global warming for selected processes. **All values in kg CO_2 equivalent**. Soil JB3 (sandy).[1]

Processes		CH_4	Biogenic CO_2 (field)	N_2O	CO_2 (fossil or biogenic not from field processes)	Total emission (kg CO_2 equivalent) for the process
Scenario A (pig)						
In-house storage		75.67	0	11.16	3.44	90.3
Outdoor storage		44.62	0	16.00	0.18	60.8
Field processes		0	88.62	34.87	2.29[b]	125.9[a]
Scenario H						
In-house storage		75.67	0	11.16	3.44	90.3
Outdoor storage	Liquid fraction	23.48	0	12.88	0[c]	38.8[a]
	Degassed biomass mixture	5.07	0	1.92	0[c]	7.7[a]
Field processes	Liquid fraction	0	49.93	26.59	1.87	78.5[a]
	Degassed biomass mixture	0	23.93	6.62	33.2	31.0[a]
Biogas production		0.84	0	0.009	0.75[b]	1.72[a]
Co-generation heat and power		1.36	0	0.01	15.26	16.8[a]
Avoided electricity production		0	0	-0.17	-14.87[b]	-16.4[a]
Avoided heat production		0	0	-0.02	-4.59[b]	-4.9[a]

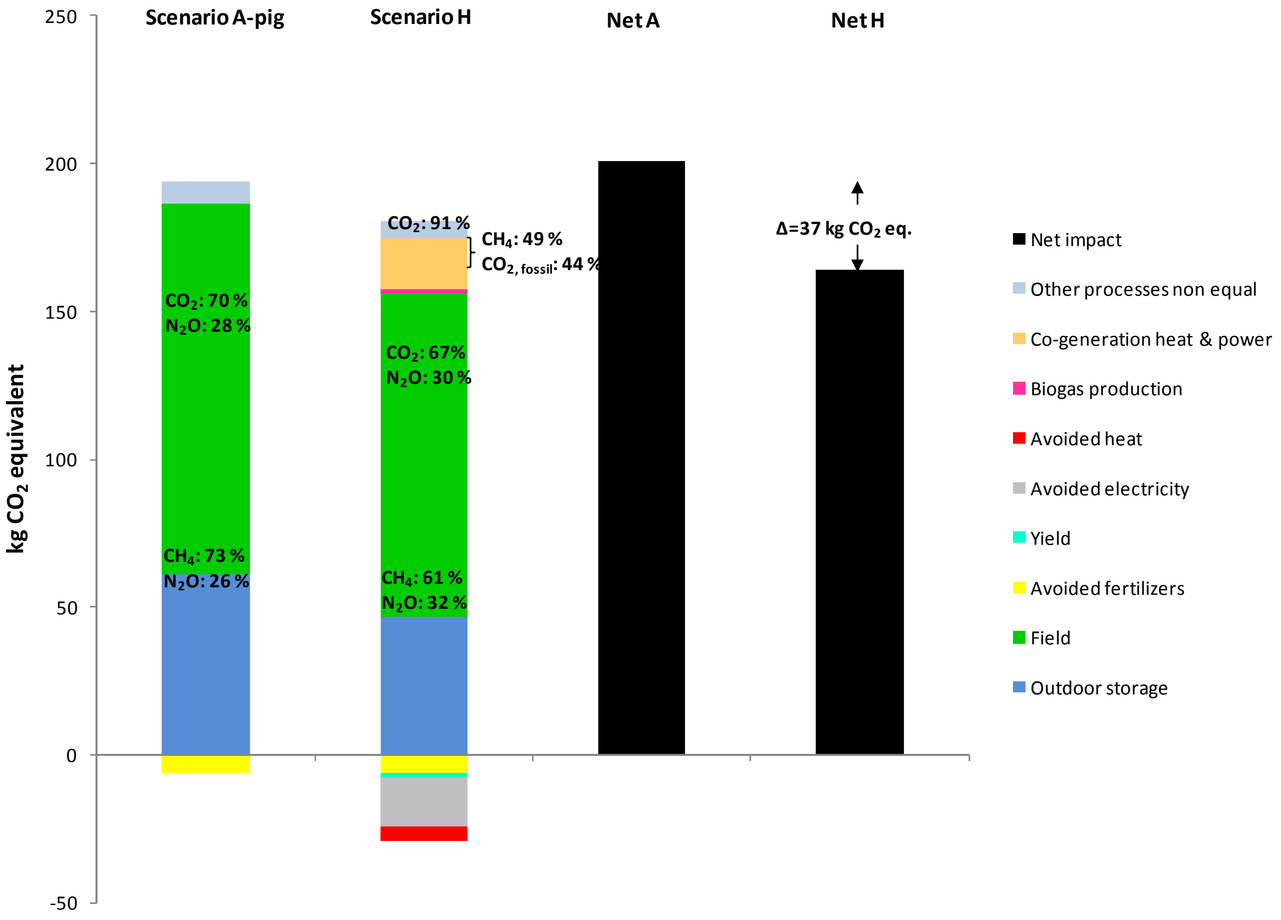
[1] The number of digits is *not* an expression of the uncertainty.
[a] The balance is from other global warming contributing substances not presented in this table.
[b] Fossil CO_2
[c] This is not a zero value

The major results as regarding global warming can be summarised as:

- Overall, managing the slurry as in Scenario H allows, based on the reference scenario considered, to reduce the contributions to global warming from slurry management.
- There are 2 major hot spots regarding global warming:
    - In-house storage of slurry. The main contributor is CH_4.
    - Field processes. The main contributor is CO_2 due to field processes. The contribution to global warming from field process is lower in the case of Scenario H as compared to Scenario A.
- Storing digested slurry has considerable benefits on global warming as compared to storage of raw slurry.
- The contributions to global warming from the use of electricity, the biogas process and the transportation are rather negligible in both scenarios.
- Both scenarios allow avoiding the contributions to global warming from the production of inorganic N, P and K fertilisers in the same magnitude.
- Scenario H allows avoiding the production of marginal heat and electricity, which has considerable benefits on global warming contributions.

This information is summarised in figure 6.3. This figure presents the contribution to climate change of Scenario A and H only for the processes that are not equal between A and H (i.e. in-house storage and avoided N fertiliser are not included). All processes are presented; the category labelled “other processes non equal” represents the aggregation of all processes not presented in the legend.

Figure 6.3.
Comparison of Scenario H vs Scenario A for global warming including carbon sequestration, for processes differing between A and F only. Soil JB3, 10 years values.



6.2.3 Acidification

As it can be observed from figure 6.2, the major contributor to acidification is in-house storage, for both scenarios. In both cases, it represents 60 % of the total positive contributions to acidification from the reference scenario. This is mostly due to one substance, namely NH_3, as discussed in section 4.2.3.

Field processes represent the other most important contributor to acidification, representing, for Scenario H, about 20 % of the total positive contributions to acidification from the reference scenario (accounting for both liquid fraction and degassed biomass). The main contributing substance in this case is also NH_3 (96 % of the contributions for this process).

The outdoor storage, if the contributions from the liquid fraction and the degassed biomass are aggregated in the case of Scenario H, contributes to acidification in the same magnitude for both scenarios (but it is a little higher for Scenario A). The main contributing substance to acidification for outdoor storage is also NH_3 (77% of the contributions for this process).

For Scenario H, as it can be observed in figure 6.2.A, the contributions to acidification from the biogas production, the co-generation of heat and power and the transportation are rather small.

As explained in section 6.2.1, the amount of fertiliser avoided is the same for both scenarios, and so is the avoided contribution to acidification from the inorganic fertilisers not produced/used.

The production of marginal heat avoided through the use of biogas for heating has a small contribution to acidification avoidance, but the production of marginal electricity avoided as well as the wheat production avoided have insignificant contributions in avoiding acidification.

Overall, when the “deductions” from the avoided contributions to acidification are accounted for, the difference between managing the slurry as described in Scenario H with the reference slurry management amount to 7.1 m^2 unprotected ecosystem (UES) (figure 6.4). When accounting for uncertainties, this difference is however not significant (figure 6.10.A)

Table 6.3 summarises, for selected processes, the contribution of the main contributing substances to acidification, for both Scenario A and H.

Table 6.3.
Scenario H vs A: Contribution of the main contributing substances to acidification for selected processes. **All values in m^2 unprotected ecosystem (UES)**. Soil JB3 (sandy).[1]

Processes		NH_3	NO_X	SO_2	Total emission (m^2 UES) for the process
Scenario A (pig)					
In-house storage		29.77	0.37	0	30.14
Outdoor storage		3.09	0.93	0	4.02
Field processes		15.25	0.34	0.06	15.66[a]
Scenario H					
In-house storage		29.77	0.37	0	30.14
Outdoor storage	Liquid fraction	2.48	0.76	0.02	3.26[b]
	Degassed biomass mixture	0.60	0.11	0.01	0.72[b]
Field processes	Liquid fraction	6.40	0.27	0.05	6.73[a]
	Degassed biomass mixture	3.16	0.06	0.01	3.23[b]
Biogas production		0[c]	0.007	0.017	0.027[a]
Co-generation heat and power		0[c]	0.85	0.08	0.93[b]
Avoided electricity production		-0.006	-0.14	-0.33	-0.53[a]
Avoided heat production		-0.002	-0.10	-0.45	-0.67[a]

[1] The number of digits is *not* an expression of the uncertainty.
[a] The balance is from other acidification contributing substances not presented in this table.
[b] This includes other contributing substances which are not reflected when contributions are presented with 2 decimal places.
[c] This is not a zero value.

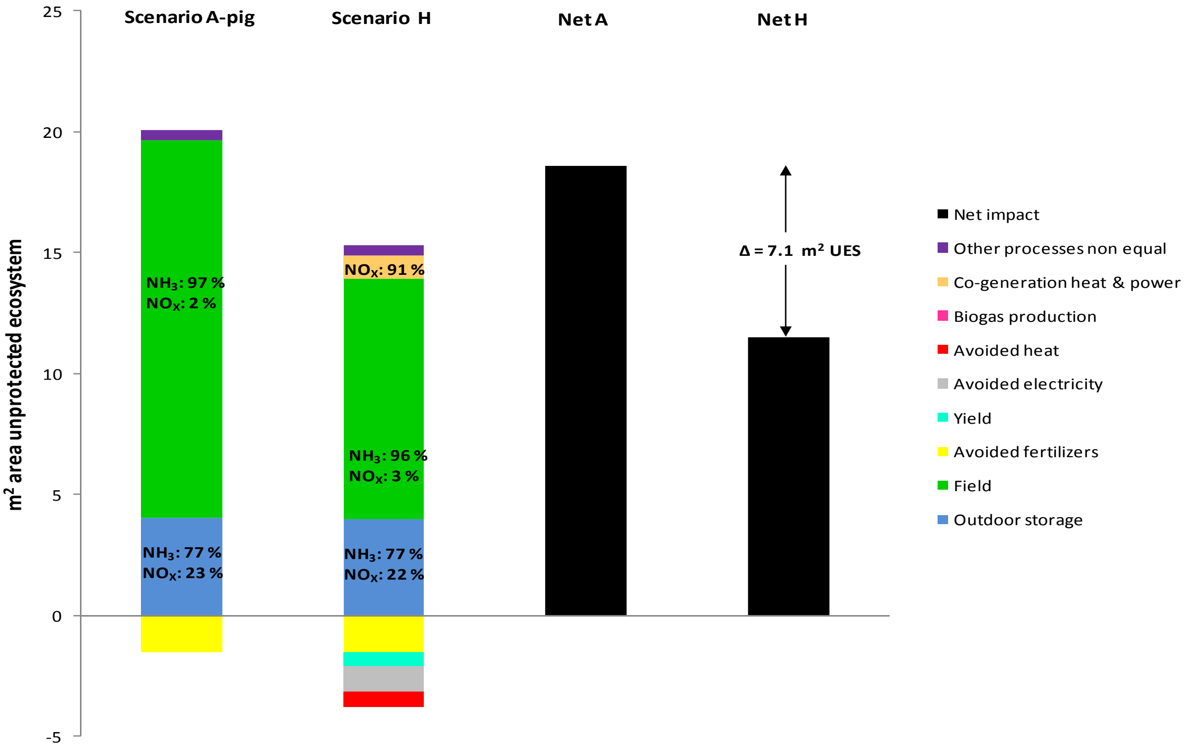
The major results as regarding acidification can be summarised as:

- Overall, managing the slurry as in Scenario H does not allow significant benefit over the reference slurry management as regarding acidification.
- There are 2 major hot spots as regarding acidification:
  - In-house storage of slurry. The main contributor is NH_3.
  - Field processes. The main contributor is NH_3.

- The overall contribution to acidification from outdoor slurry storage is similar for both Scenario A and H, and NH_3 is the main contributor.

This information is summarised in figure 6.4. This figure presents the contribution to acidification of Scenarios A and H only for the processes that are not equal between A and H (i.e. in-house storage and avoided N fertiliser are not included). All processes are presented; the category labelled “other processes non equal” represents the aggregation of all processes not presented in the legend.

Figure 6.4.
Comparison of Scenario H vs Scenario A for acidification, for processes differing between A and H only. Soil JB3, 10 years values.



6.2.4 Aquatic eutrophication (N)

Aquatic N eutrophication is, as illustrated in figure 6.2.A, mostly due to field processes:

- For Scenario A, this represents 81 % of the total positive contributions to N-eutrophication from the reference scenario;
- For Scenario H, this represents 79 % of the total positive contributions to N-eutrophication from the reference scenario;

The percentages above considers 10 years value as regarding the horizon for C during field processes, these percentages are higher if 100 years values are considered, as presented in table 6.1.

The contribution to N-eutrophication from field processes is therefore similar for both scenarios. In both case, it is essentially caused by N leaching through soils.

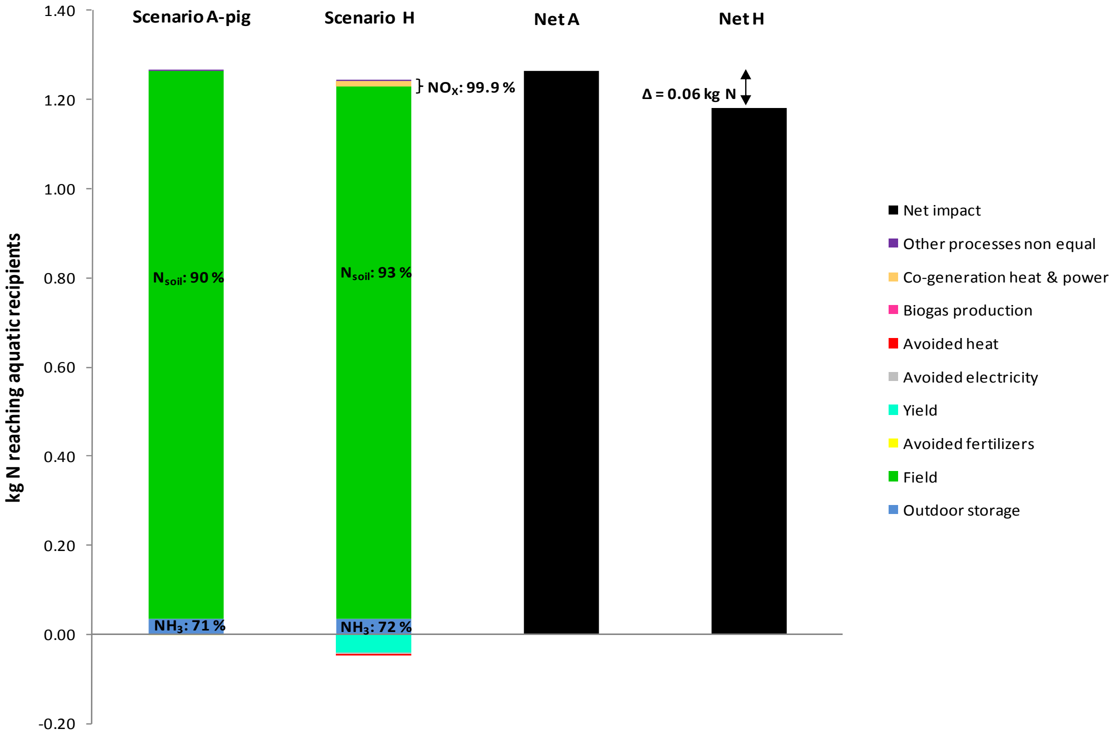
Figure 6.2 illustrates that the contribution to N-eutrophication from Scenario H is much alike the contributions from the reference scenario. However, when the 100 years values are taken into account as regarding the horizon time for

C during field processes, the gain created by avoided wheat in Scenario H becomes more significant, in which case Scenario H appears slightly more advantageous than the reference scenario.

Overall, when the “deductions” from the avoided contributions to N-eutrophication are accounted for, managing the slurry as described in Scenario H present a difference of 0.07 kg N reaching aquatic recipients as compared to the reference scenario. This is for the 10 years value for C. Taking the 100 years values for C during field processes into account, the difference is 0.08 kg N. However, when accounting for uncertainties, there are no significant benefits (figure 6.10.A).

This information is summarised in figure 6.5. This figure presents the contribution to N-eutrophication of Scenarios A and H only for the processes that are not equal between A and H (i.e. in-house storage and avoided N fertiliser are not included). All processes are presented; the category labelled “other processes non equal” represents the aggregation of all processes not presented in the legend.

Figure 6.5.
Comparison of Scenario H vs Scenario A for N-eutrophication, for processes differing between A and H only. Soil JB3, 10 years values.



6.2.5 Aquatic eutrophication (P)

As it can be observed from figure 6.2.A and table 6.1, the contribution (positive and negative) to P-eutrophication are about the same for both scenarios. In fact, the only difference is the extra avoided heat, electricity and wheat production avoided in Scenario H, but all together they represent a minor magnitude.

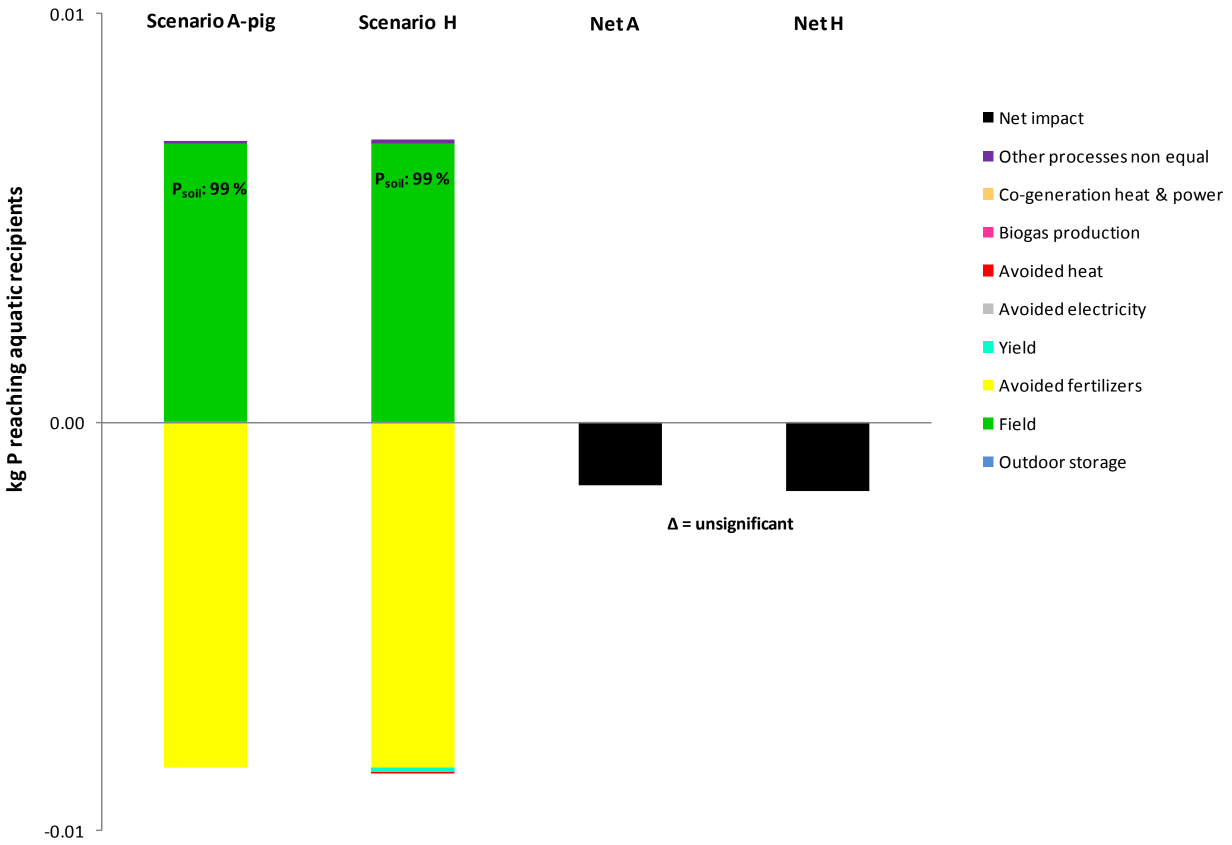
The major positive contribution to this impact is field processes (through P leaching in soils which represents 99 % of the contributions from this process in both scenarios) and the major negative contribution is the inorganic P fertiliser avoided.

For Scenario H, it can be highlighted that, for the field processes, the liquid fraction contribute to about 79 % of the total positive contributions to eutrophication (P) from the reference scenario, while it is 21 % for the degassed biomass mixture. This difference reflects the important difference between the mass flow of these 2 fractions in the system; while there is 888.5 kg liquid fraction ex-storage (including water) per 1000 kg ex-animal, there is only 187.7 kg degassed biomass ex storage (including water) per 1000 kg ex-animal.

For both fractions, it was considered that P leaching to soils corresponds to 10 % of the P applied to field, and 6 % of this has the possibility to reach aquatic recipients (based on Hauschild and Potting, 2005). This is detailed in sections H.7 and H.22 of Annex H. This assumption involves some uncertainties, as discussed in section 4.2.5.

Overall, when the “deductions” from the avoided contributions to P-eutrophication are accounted for, managing the slurry as described in Scenario H does not allow a significant benefit for P-eutrophication over managing the slurry as in the reference scenario. This is illustrated in figure 6.6 and 6.10.A.

Figure 6.6.
Comparison of Scenario H vs Scenario A for P-eutrophication, for processes differing between A and H only. Soil JB3, 10 years values.



6.2.6 Photochemical ozone formation ("smog")

In both scenarios, there are 2 main hot spots for photochemical ozone formation:

- In-house storage, representing about 56 % of the total positive contributions to photochemical ozone from the reference scenario (for both Scenario A and H).
- Outdoor slurry storage:
  - Scenario A: this process represents 39 % of the positive contributions from the reference scenario;
  - Scenario H: this process represents 27 % of the positive contributions from the reference scenario.

In the case of in-house storage, the main contributor is CH_4, which represents about 95 % of the contribution to ozone formation for this process. Concerns regarding potential overestimation of in-house CH_4 are discussed in section 4.2.6 and 4.2.2.

Methane is also the main contributing substance to ozone formation for the outdoor slurry storage process (81 % in the case of Scenario A and 75 % in the case of Scenario H). The fact that the overall contribution from outdoor storage is lower for Scenario H reflects the effect of the digestion. This is due to the lower VS content of degassed slurry, thus involving a much lower potential for CH_4 emissions. This again highlights the positive effect of slurry digestion as regarding CH_4 emissions during slurry storage.

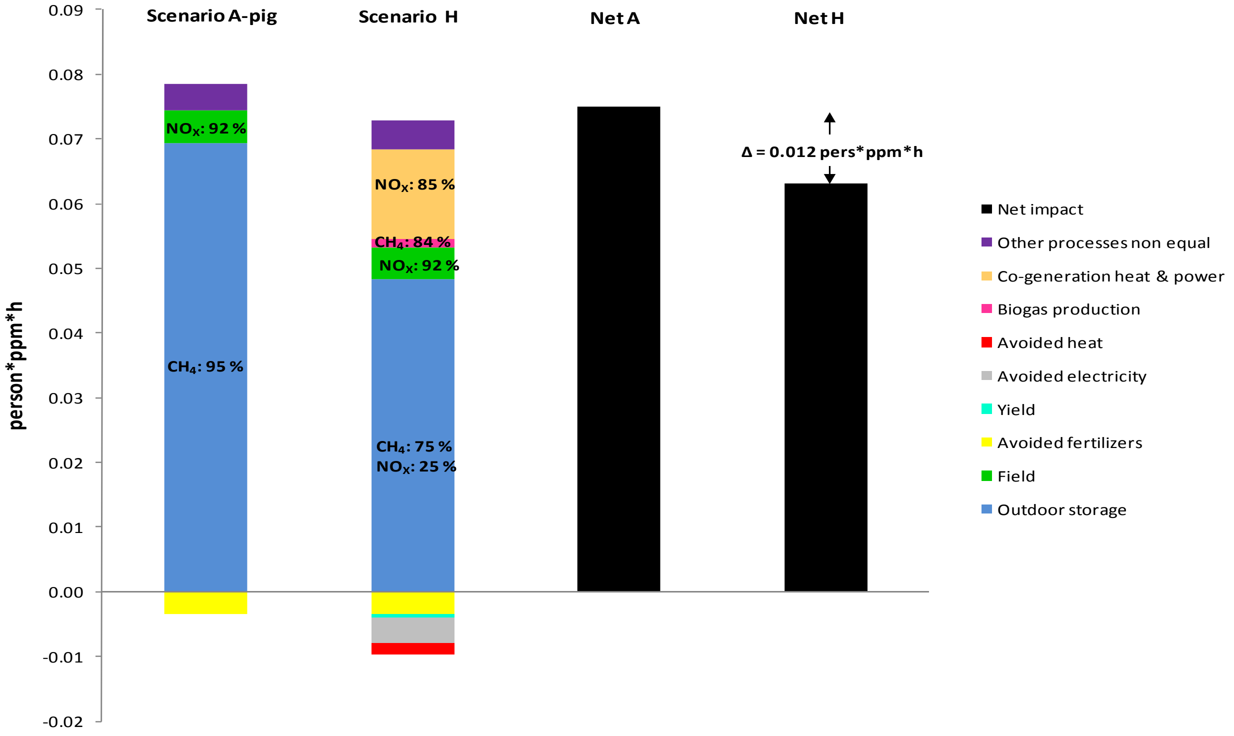
Another contributing process to this impact category is, for Scenario H, the co-generation of heat and power. The main contributing substance in this case is NO_x (85 % of the total contributions for this process), which is emitted during the combustion of the biogas in the biogas engine.

Avoiding marginal heat and electricity to be produced only have a minor contribution in avoiding the photochemical ozone formation. Avoiding inorganic fertilisers to be used/produced does contribute in reducing the overall ozone formation impact, in similar magnitude for both scenarios.

Overall, when the "deductions" from the avoided contributions photochemical ozone formation are accounted for, managing the slurry as described in Scenario H present a difference of 0.012 pers*ppm*h as compared to the reference scenario. When the uncertainties are taken into account, this benefit is not significant (figure 6.10.A)

This information is summarised in figure 6.7. This figure presents the contribution to photochemical ozone formation of Scenarios A and H only for the processes that are not equal between A and H (i.e. in-house storage and avoided N fertiliser are not included). All processes are presented; the category labelled "other processes non equal" represents the aggregation of all processes not presented in the legend.

Figure 6.7.
Comparison of Scenario H vs Scenario A for photochemical ozone formation, for processes differing between A and H only. Soil JB3, 10 years values.



6.2.7 Respiratory inorganics (small particles)

Respiratory inorganics is caused by 3 main processes:

- In-house storage of slurry: this process represents 56 % of the total positive contributions to respiratory inorganics from the reference scenario (for both Scenario A and H).
- Field processes:
    - Scenario A: this process represents 30 % of the total positive contributions to respiratory inorganics from the reference scenario
    - Scenario H: this process represents 20 % of the total positive contributions to respiratory inorganics from the reference scenario
- Outdoor slurry storage:
    - Scenario A and H: this process represents about 10 % of the total positive contributions to respiratory inorganics from the reference scenario

For in-house storage, the main contributor is NH_3 emissions, representing about 97 % of the contribution to respiratory inorganics for this process.

For field process, the main contributing substance to respiratory inorganics is also NH_3 (contributing to about 91 % in Scenario A and 87 % in Scenario H for this process).

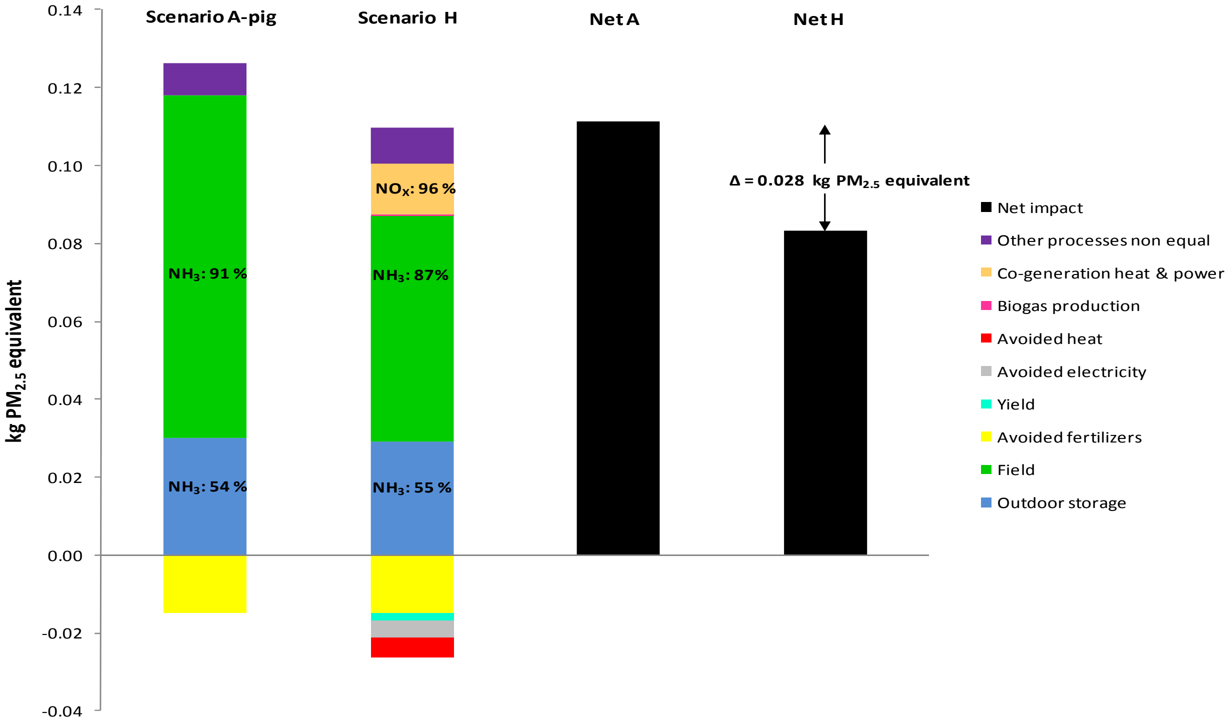
For outdoor storage, the contributions are divided between NH_3 and NO_X. In the case of Scenario H, the co-generation of heat and power, i.e. when the biogas is burnt in the biogas engine, also contributes to “respiratory inorganics” formation, representing 4.5 % of the total positive contributions to respiratory inorganics from the reference scenario.

Avoiding marginal heat and electricity to be produced only have a minor contribution in avoiding respiratory inorganics. This observation also applies for the avoided wheat production induced by the extra yield. Avoiding inorganics fertilisers to be produced does contribute to avoid “respiratory inorganics” formation, in similar magnitude for both scenarios.

Overall, when the “deductions” from the avoided contributions to “respiratory inorganics” are accounted for, managing the slurry as described in Scenario H present a difference of 0.028 kg $PM_{2.5}$ equivalent as compared to the reference scenario. This difference is not significant when accounting for uncertainties (figure 6.10.A).

This information is summarised in figure 6.8. This figure presents the contribution to “respiratory inorganics” of Scenarios A and H only for the processes that are not equal between A and H (i.e. in-house storage and avoided N fertiliser are not included). All processes are presented; the category labelled “other processes non equal” represents the aggregation of all processes not presented in the legend.

Figure 6.8.
Comparison of Scenario H vs Scenario A for "respiratory inorganics", for processes differing between A and H only. Soil JB3, 10 years values.



6.2.8 Non-renewable energy resources

Both scenarios contribute to the use of the non-renewable energy through the use of marginal electricity, of liquid fuel for transportation (road and tractors) and the use of marginal heat. This is reflected in figure 6.2.B where the contributing processes are those requiring electricity or fuel inputs.

Avoiding marginal electricity but also heat to be produced through the use of biogas for scenario H allows a considerable "avoidance" of non-renewable energy to be used. This is also true for the fertilisers avoided, but the magnitude of this is similar for both scenarios. The wheat production avoided in Scenario H through the yield increase also contributes to avoid, in a rather small magnitude, the use of non-renewable energy resources.

Overall, the difference between Scenario H and the reference scenario lies mostly in the avoided contributions rather than in the positive contributions. This is why, as explained in section 4.2.8, using less electricity or heat input for the biogas process (as suggested in Annex F, section F.15.3) would not contribute to a drastic change of the situation for this impact category, given the larger importance of the avoided contributions.

Managing the slurry as described in Scenario H thus offers a significant advantage over the reference management, as regarding the impact on non-renewable energy use. Overall, when the "deductions" from the avoided contributions to non-renewable energy use are accounted for, managing the slurry as described in Scenario H allows a reduction of 266 MJ of (primary) non-renewable energy use as compared to the reference scenario.

6.2.9 Consumption of phosphorus as a resource

Both scenarios allows about the same amount of P to be preserved as a resource (through the avoidance of inorganic P fertiliser to be produced). The wheat production avoided in Scenario H (induced by the increased yield) is an extra as compared to the reference scenario but has a rather insignificant contribution in P consumption avoidance, as it can be seen it table 6.1 and figure 6.2.A.

6.2.10 Carbon stored in soils

Through Scenario H, a certain amount of C ends up to be stored in soils, which means this C is not emitted as CO_2. This is through the C of the different slurry fractions that is applied to field and not emitted as CO_2.

For the reference scenario, a total of 3.61 kg C per 1000 kg pig slurry ex-animal is stored in soils, corresponding to 13.2 kg CO_2 not emitted per functional unit. This is considering a horizon of 10 years. With the 100 years values, more CO_2 is emitted and consequently less C is stored per functional unit (1.03 kg), resulting to 3.8 kg CO_2 not emitted per 1000 kg pig slurry ex-animal. These values are presented in table 4.1 of Wesnæs et al. (2009).

For Scenario H, less C is added to field per functional unit but also less CO_2 is overall emitted. As a result, the amount of C sequestrated in the soil per functional unit (3.48 kg C considering 10 years values; 0.64 kg C considering 100 years values) is similar to the amount of C sequestrated for the reference scenario. In terms of CO_2 avoided, this correspond to 12.7 kg CO_2 (10 years values) and 2.4 kg CO_2 (100 years values) per 1000 kg pig slurry ex-animal.

6.3 Uncertainties

The uncertainties on the compared results have been estimated by analysing the most important factors that are ***changed***, when comparing scenario H with the reference scenario A. It means that the uncertainties for each scenario is not analysed as such, but only the emissions that are important for the ***differences***. The uncertainties on the comparisons are based on estimates of the uncertainties on those emissions that are most important for the changes.

The uncertainties are related to the total positive contributions from the reference scenario A (i.e. the total that is set to 100% in figures 6.3 and 6.4 as “index”).

The values of the uncertainty ranges are shown in table 6.4.

6.4 Synthesis of the results for all impact categories assessed

Table 6.4 compares the overall characterised results of Scenario A versus Scenario H, for all impacts categories (including carbon stored in soils). It also presents the uncertainty ranges for all impact category results.

Figures 6.9.A and 6.9.B illustrate the results presented in table 6.4, and give an impression of the uncertainty. The difference between these two figures is the axis, which has a greater range in the case of figure 6.9.B in order to capture the whole impacts of non-renewable energy consumption. Figures 6.10.A and 6.10.B present only the net differences between Scenario A and H, including the uncertainties.

Table 6.4.
Comparison of the impacts from Scenario A (reference) versus Scenario H (biogas from raw pig slurry + fibre fraction from mechanical separation). The number of digits is *not* an expression of the uncertainty.

Impact category	Scenario A - pig	Scenario H	Difference, i.e. Biogas scenario H minus Reference scenario A	Conclusion
Global warming (during 10 years) [kg CO_2 eq.]				
Positive contributions: Negative contributions: Net:	+284 kg - 36 kg = 248 kg	+ 271 kg - 59 kg = 211 kg	-37 [-55 to -18] kg CO_2 eq.	6-19% reduction of positive contributions from scenario A
Global warming (during 100 years) [kg CO_2 eq.]				
Positive contributions: Negative contributions: Net:	+ 304 kg - 47 kg = 257 kg	+ 293 kg - 72 kg = 220 kg	-37 [-55 to -19] kg CO_2 eq.	6-18% reduction of positive contributions from scenario A
Acidification [m^2 UES, i.e. area of unprotected ecosystem]				
Positive contributions: Negative contributions: Net:	+ 50.3 m^2 -5.5 m^2 = 44.8 m^2	+ 45.5 m^2 -6.9 m^2 = 38.5 m^2	-6.2 [-16 to +3] m^2 UES	No significant difference due to uncertainties
N-eutrophication (aquatic) (during 10 years) [kg N - amount reaching aquatic recipients]				
Positive contributions: Negative contributions: Net:	+ 1.51 kg - 0.93 kg = 0.59 kg	+ 1.49 kg - 0.97 kg = 0.52 kg	-0.06 [-0.19 to +0.06] kg N	No significant difference due to uncertainties
N-eutrophication (aquatic) (during 100 years) [kg N - amount reaching aquatic recipients]				
Positive contributions: Negative contributions: Net:	+ 1.63 kg - 1.03 kg = 0.61 kg	+ 1.65 kg - 1.11 kg = 0.53 kg	-0.07 [-0.22 to +0.07] kg N	No significant difference due to uncertainties
P-eutrophication (aquatic) [kg P - amount reaching aquatic recipients]				
Positive contributions: Negative contributions: Net:	+ 0.0069 kg - 0.0086 kg = -0.0017 kg	+ 0.0069 kg - 0.0087 kg = -0.0018 kg	-0.0001 [-0.0004 to 0.0001] kg P	No significant difference due to uncertainties
Photochemical ozone formation [person.ppm.hr - see section 3.4.7]				
Positive contributions: Negative contributions: Net:	+ 0.179 p.p.h - 0.014 p.p.h = 0.17 p.p.h	+ 0.17 p.p.h -0.02 p.p.h = 0.15 p.p.h	-0.012 [-0.036 to +0.012] p.p.h	No significant difference due to uncertainties
Respiratory Inorganics [kg PM2.5 eq, i.e. kg equivalents of 2.5 µm size particles]				
Positive contributions: Negative contributions: Net:	+ 0.29 kg - 0.05 kg = 0.24 kg	+ 0.27 kg - 0.06 kg = 0.21 kg	-0.028 [-0.084 to +0.028] kg PM2.5	No significant difference due to uncertainties
Non-renewable energy [MJ primary energy]				
Positive contributions: Negative contributions: Net:	+ 151 MJ -369 MJ = -217 MJ	+ 194 MJ -677 MJ = -483 MJ	-270 [-350 to -190] MJ	125-230% reduction of positive contributions from scenario A
Phosphorus Resources [kg P]				
Positive contributions: Negative contributions: Net:	0 kg - 1.34 kg = -1.34 kg	+ 0 kg - 1.35 kg = -1.35 kg	-0.01 [-0.026 to 0) kg P	No significant difference due to uncertainties
Carbon stored in soil during 10 years [kg C] **and corresponding amount of CO_2-eq**				
C added with slurry: C lost as CO2: C stored in soil: Net CO2:	+ 31.7 kg C -28.1 kg C = 3.6 kg C = 13.2 kg CO_2	+ 27.6 kg C - 24.1 kg C = 3.5 kg C = 12.7 kg CO2	-0.14 [-1.2 to +0.9] kg C -0.5 [-4.5 to +3.5] kg CO2	No significant difference due to uncertainties
Carbon stored in soil during 100 years [kg C] **and corresponding amount of CO_2-eq**				
C added with slurry: C lost as CO2: C stored in soil: Net CO2:	+ 31.7 kg C -30.7 kg C = 1.0 kg C = 3.8 kg CO_2	+ 27.6 kg C - 27 kg C = 0.64 kg C = 2.4 kg CO_2	-0.14 [-1.2 to +0.9] kg C -0.5 [-4.5 to +3.5] kg CO2	No significant difference due to uncertainties

Note: All numbers are all rounded and accordingly, if the reader calculates the difference, it might vary slightly from the numbers shown in the table.

Figure 6.9.A
Comparison of the environmental impacts from Scenario A (reference) versus Scenario H (biogas from raw pig slurry + fibre fraction from mechanical separation). Axis ranging from -180 to 120.

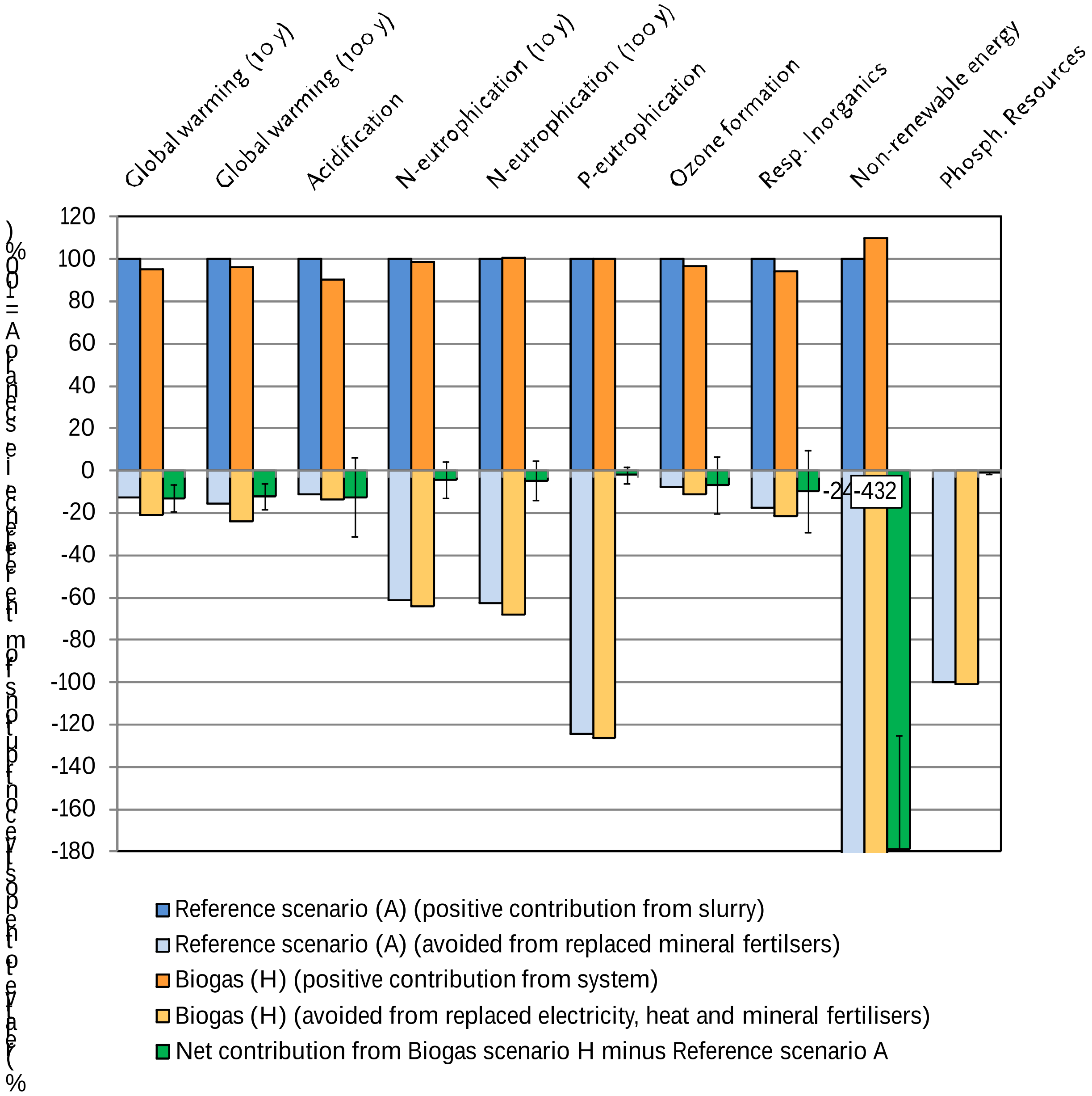


Figure 6.9.A
Comparison of the environmental impacts from Scenario A (reference) versus Scenario H (biogas from raw pig slurry + fibre fraction from mechanical separation). Axis ranging from -1000 to 200.

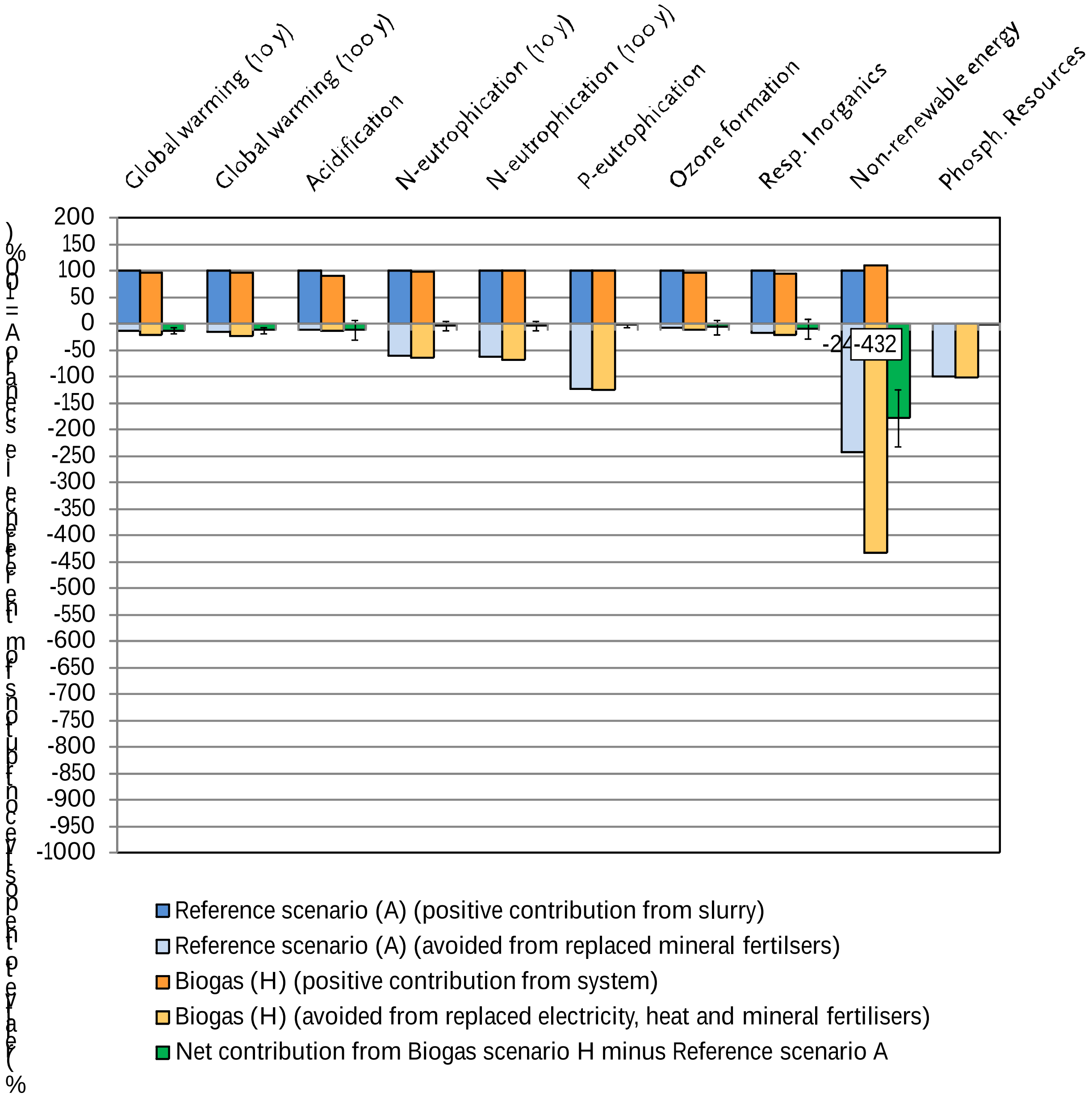


Figure 6.10.A
Comparison of the environmental impacts from Scenario A (reference) versus Scenario H (biogas from raw pig slurry + fibre fraction from mechanical separation). Net difference only. Axis ranging from -100 to 100.

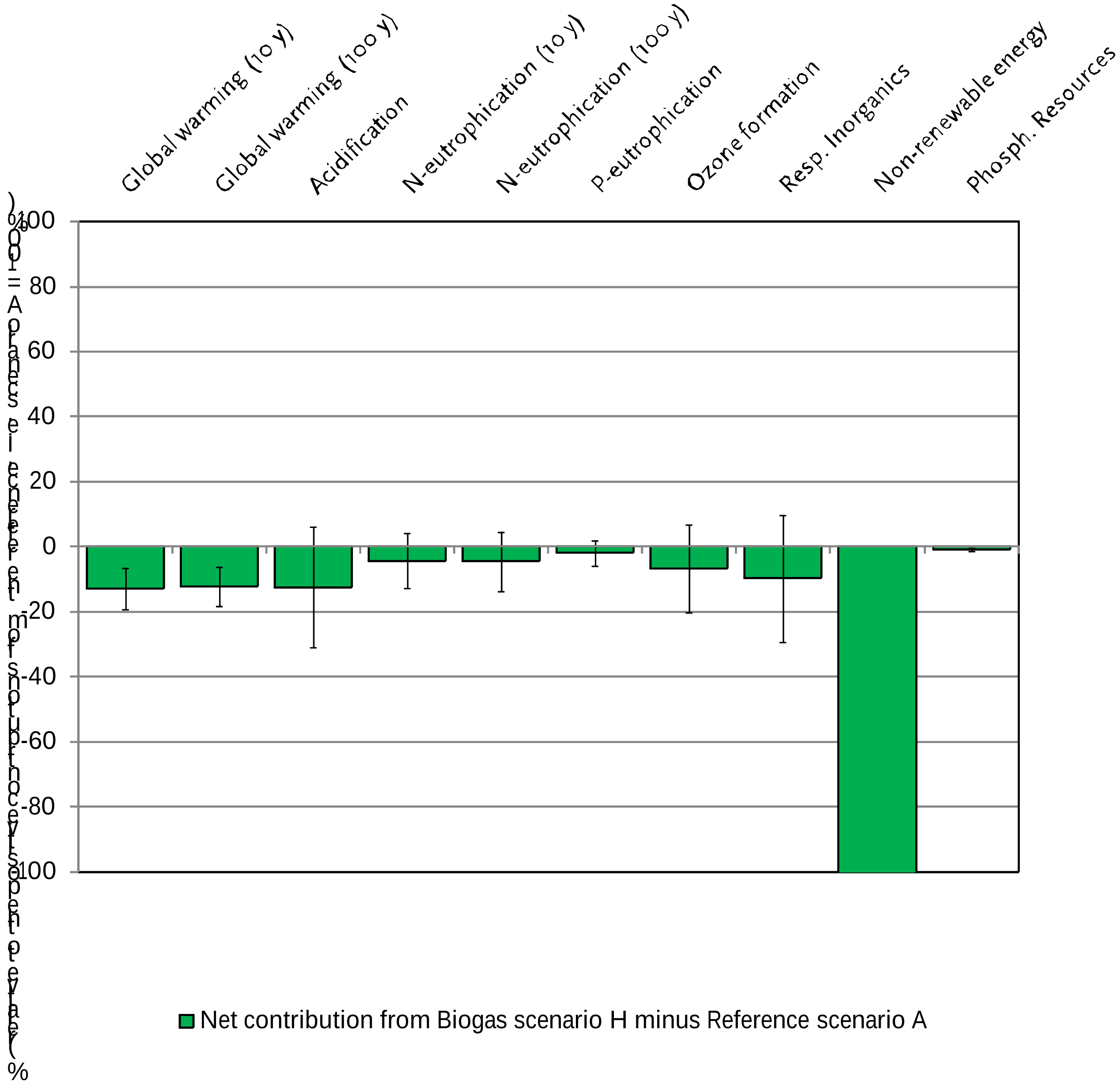
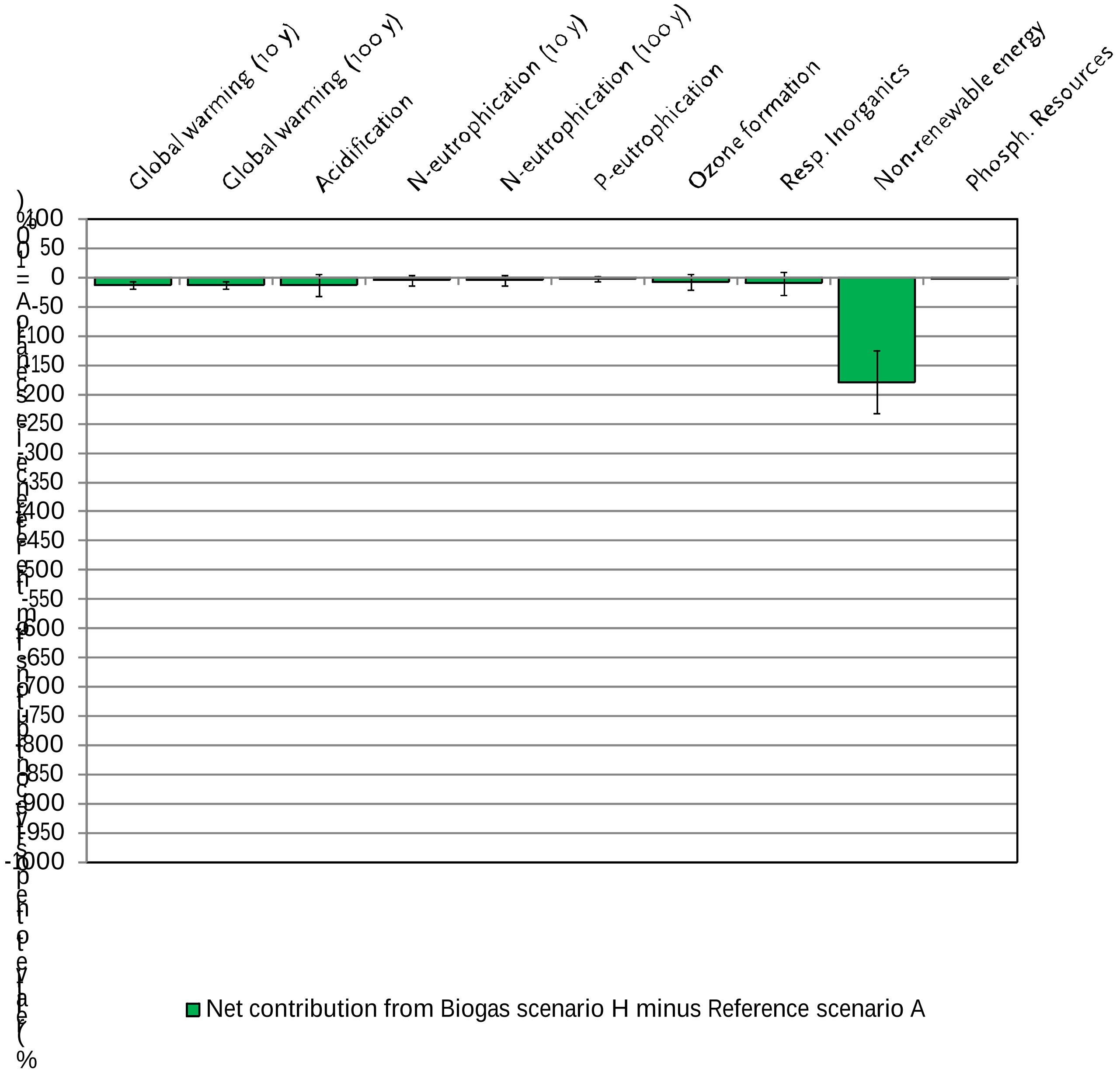


Figure 6.10.B
Comparison of the environmental impacts from Scenario A (reference) versus Scenario H (biogas from raw pig slurry + fibre fraction from mechanical separation). Net difference only. Axis ranging from -1000 to 100.



7 Biogas production from raw pig slurry and fibre pellets (Scenario I) – results and interpretation

This section presents the results and the interpretation from the life cycle assessment carried out for “Scenario I”. The results from “Scenario I” are compared to those of the reference scenario for fattening pig slurry management, i.e. “Scenario A”. The life cycle assessment is performed in order to answer the research question: ***“What are the environmental benefits and disadvantages of utilising pig slurry for producing fibre pellets and utilising the fibre pellets for biogas production - compared to the reference scenario for pig slurry?”***.

As for Scenario H, the present scenario does not relies on “best available technologies” or “best possible practices” as it was the case for Scenarios F and G.

The detailed description of this scenario, including all mass balances, assumptions and calculations, is presented in Annex I. All life cycle inventory data used for the results presented in this section can therefore be found in Annex I.

The environmental impacts and conclusions in this section to a great extent build on data and information delivered by the producer of the technology, Samson Bimatech, and on data made from Samson Bimatech (laboratory measurements of the slurry composition), combined with data for biogas production based on information from Xergi. The conclusions made in this section rely on this information, and the authors of this study have not had the possibility of verifying the data.

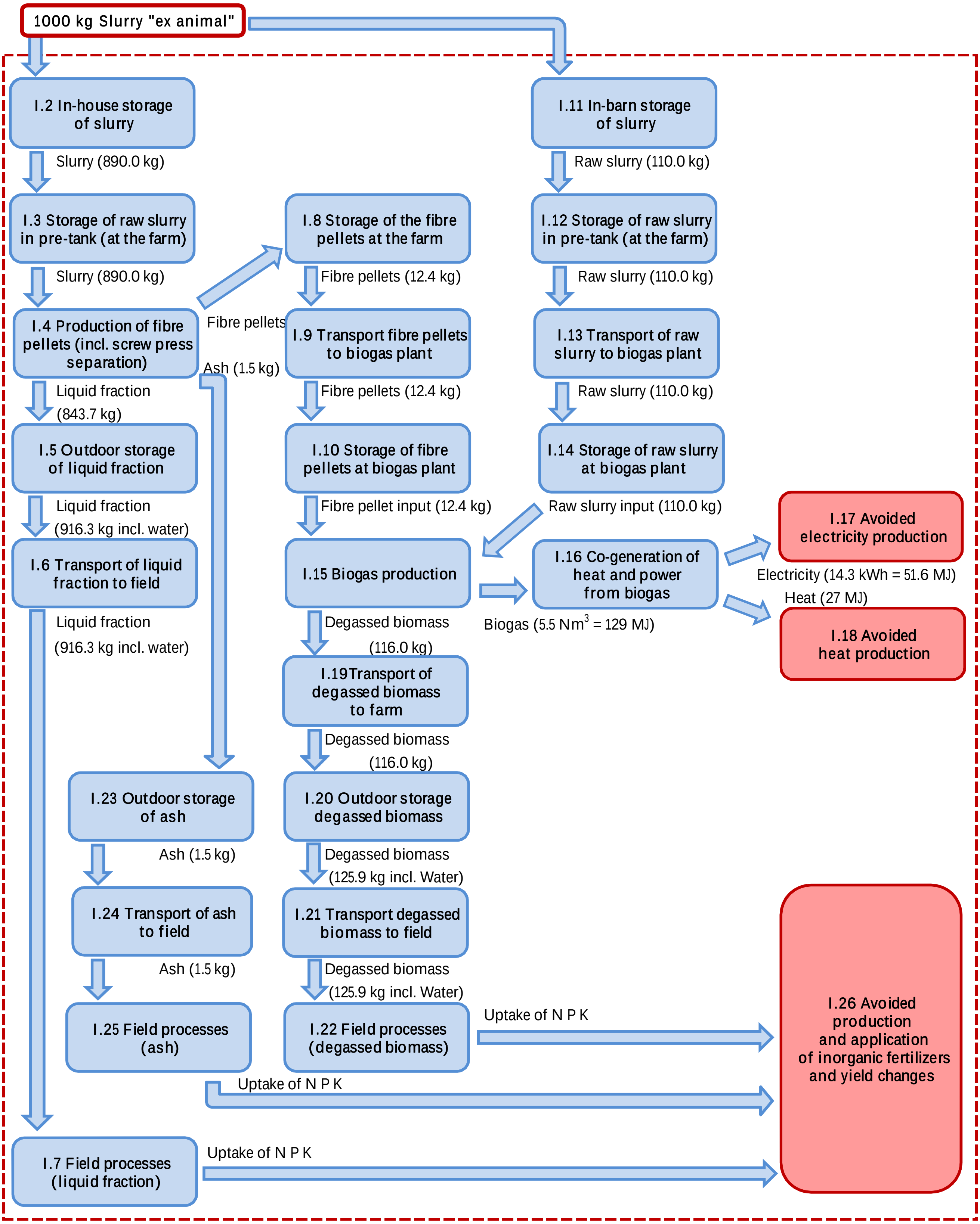
7.1 System description

The system constituting Scenario I, as described in section 2.2.5, consists to use pig slurry for the production of fibre pellets, and these fibre pellets are used for biogas production in a mixture with raw pig slurry.

After excretion, raw slurry is stored in-house; part of it is separated and part of it is kept as raw slurry. The separation process used is the same mechanical separation technology as used for Scenario H. The fibre fraction from this separation is used as an input for producing fibre pellets, while the liquid fraction is used as an organic fertiliser. The production of pellets also involves the production of ashes which are used on-field as an organic fertiliser. The pellets and un-separated raw slurry are used for biogas production. The biogas produced is used for co-production of heat and power. The degassed biomass effluent resulting from the anaerobic digestion process is stored and used on-field as an organic fertiliser.

The flow of the pig slurry “from farm to soil” is shown in figure 7.1. The process numbers refer to the heading of the sections in Annex I.

Figure 7.1.
Process flow diagram for “scenario I” – biogas production from raw pig slurry and fibre pellets. The process numbers follows the numbers of the sections in annex I.



7.2 Results of the Impact Assessment

7.2.1 Overall results of the comparison

Table 7.1 presents the overall environmental impacts from “Scenario I” (biogas from raw pig slurry and fibre pellets) and compare them to the environmental impacts from the reference scenario for pig slurry (described in section 3). Figures 7.2 A and 7.2.B illustrate the results presented in table 7.1. Figures 7.2 A and 7.2.B are identical except for the minimum and maximum at the x-axis. In the case of figure 7.2.B, the minimum and maximum were adjusted in order to present the full impacts covered for the consumption of non-renewable energy impact category. As in previous sections, results are presented for soil JB3 only (sandy soil).

As explained in section 4.2.1, the results presented are “characterised” results and are expressed, for each impact categories, relative to the result of the reference scenario. The positive values are the contributions to the environmental impacts and resource consumptions by the slurry management scenarios. The negative values are “avoided environmental impacts”.

Results presented in table 7.1 should be interpreted with care in the light of the assumptions and data that were used to obtain them, i.e. the life cycle inventory data presented in Annex I. An attempt to discuss these results based on this focus, impact category per impact category, is presented in sections 7.2.2 to 7.2.10.

Table 7.1.

Scenario I vs A: Contribution of the different processes to each environmental impact categories selected. Results, for each impact category, are expressed in % of the total positive contributions from the reference scenario (considering the 10 years values, when this applies). Soil JB3 (sandy)[1]

Impact Categories	GW (10 y)	GW (100 y)	Acidification	Eutrophication (N) (10 y)	Eutrophication (N) (100 y)	Eutrophication (P)	Ozone formation	Respiratory inorganics	Non-renewable energy	Phosphorus resources
SCENARIO A - pig										
A.2 In-house storage	31.7	31.7	60.0	16.3	16.3	0.0	56.2	56.2	0.0	0.0
A.3 Outdoor storage - elect	1.4	1.4	0.3	0.0[a]	0.0[a]	0.0[a]	0.5	0.4	37.0	0.0[a]
A.3 Outdoor storage	21.4	21.4	8.0	2.4	2.4	0.0	38.7	10.4	0.0	0.0
A.4 Transport to field	1.2	1.2	0.6	0.2	0.2	1.1	1.8	2.5	36.8	0.0[a]
A.5 Field processes	44.3	51.2	31.1	81.1	89.1	98.8	2.8	30.5	26.2	0.0[a]
A.6 N fertiliser	-10.6	-14.3	-7.9	-61.1	-67.7	-1.8	-5.8	-12.1	-170.1	0.0[a]
A.6 P fertiliser	-1.5	-1.5	-2.8	-0.1	-0.1	-121.8	-1.3	-4.5	-51.2	-99.9
A.6 K fertiliser	-0.6	-0.6	-0.2	0.0[a]	0.0[a]	-0.5	-0.6	-0.7	-22.2	-0.1
Sum of positive contributions	***100***	***107***	***100***	***100***	***108***	***100***	***100***	***100***	***100***	***0.0[a]***
Sum of negative contributions	***-13***	***-16***	***-11***	***-61***	***-68***	***-124***	***-8***	***-17***	***-244***	***-100***
SCENARIO I										
I.2 + I.11 In-house storage	31.7	31.7	60.0	16.3	16.3	0.0	56.2	56.2	0.0	0.0
I.3 + I.12 Pre-tank storage	0.5	0.5	0.1	0.0[a]	0.0[a]	0.0[a]	0.2	0.1	12.6	0.0[a]
I.4 Fibre pellets production in Energy plant (incl. Separation)	10.5	10.5	3.5	1.1	1.1	0.3	12.1	8.8	126.2	0.0[a]
I.5 Outdoor storage liquid fraction	14.1	14.1	6.7	2.0	2.0	0.0[a]	23.2	8.7	9.1	0.0[a]
Transport (I.6, I.9, I.13, I.19, I.21, I.24)	1.3	1.3	0.7	0.2	0.2	1.2	2.0	2.7	40.2	0.0[a]
I.7 Field processes (liquid fraction)	28.5	34.3	13.8	66.4	73.4	80.0	2.3	14.3	22.1	0.0[a]
I.8 Storage fibre pellets on-farm	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.0[a]
I.10 Storage fibre pellets biogas pl.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
I.14 Storage raw slurry biogas plant	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
I.15 Biogas production	0.4	0.4	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.5	0.1	5.4	0.0[a]
I.16 Co-generation heat and power	4.2	4.2	1.3	0.4	0.4	0.0[a]	5.5	3.2	0.8	0.0[a]
I.17 Avoided electricity production	-4.1	-4.1	-0.7	-0.1	-0.1	-0.1	-1.5	-1.1	-106.2	0.0[a]
I.18 Avoided heat production	-1.2	-1.2	-1.0	-0.1	-0.1	-0.2	-0.7	-1.3	-23.3	0.0[a]
I.2o Storage degassed biomass	1.8	1.8	1.0	0.3	0.3	0.0[a]	3.0	1.2	2.5	0.0[a]
I.22 Field processes (degassed biomass)	7.4	8.7	4.5	10.1	12.5	15.7	0.3	4.3	3.0	0.0[a]
I.23 Outdoor storage (ashes)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
I.25 Field processes (ashes)	0.0[a]	0.0[a]	0.0[a]	0.0[a]	0.0[a]	3.2	0.0[a]	0.0[a]	0.0[a]	0.0[a]
I.26 N fertiliser – production & application on JB3	-10.7	-14.3	-8.0	-61.4	-68.0	-1.8	-5.8	-12.2	-170.8	0.0[a]
I.26 P fertiliser – production & application on JB3	-1.5	-1.5	-2.8	-0.1	-0.1	-121.8	-1.3	-4.5	-51.2	-99.9
I.26 K fertiliser – production & application on JB3	-0.6	-0.6	-0.2	0.0[a]	0.0[a]	-0.5	-0.6	-0.7	-22.2	-0.1
I.26 Yield changes	-0.4	-1.0	-0.3	-1.7	-3.7	-1.2	-0.2	-0.4	-4.1	-0.6
Sum of positive contributions	***100***	***108***	***92***	***97***	***106***	***100***	***105***	***100***	***222***	***0.0[a]***
Sum of negative contributions	***-19***	***-23***	***-13***	***-63***	***-72***	***-126***	***-10***	***-20***	***-378***	***-101***

[1] The number of digits is not an expression of the uncertainty. All numbers are all rounded and accordingly, if the reader calculates the sum or the difference, it might vary slightly from the numbers shown in the table.

[a] This number is not a zero value.

Figure 7.2.a

Overall environmental impacts for the selected environmental impacts categories – Scenario I vs Scenario A. Fattening pig slurry management. Soil type JB3. 10 and 100 years time horizon for global warming and for aquatic eutrophication (N). Axis ranging from -140 to 120.

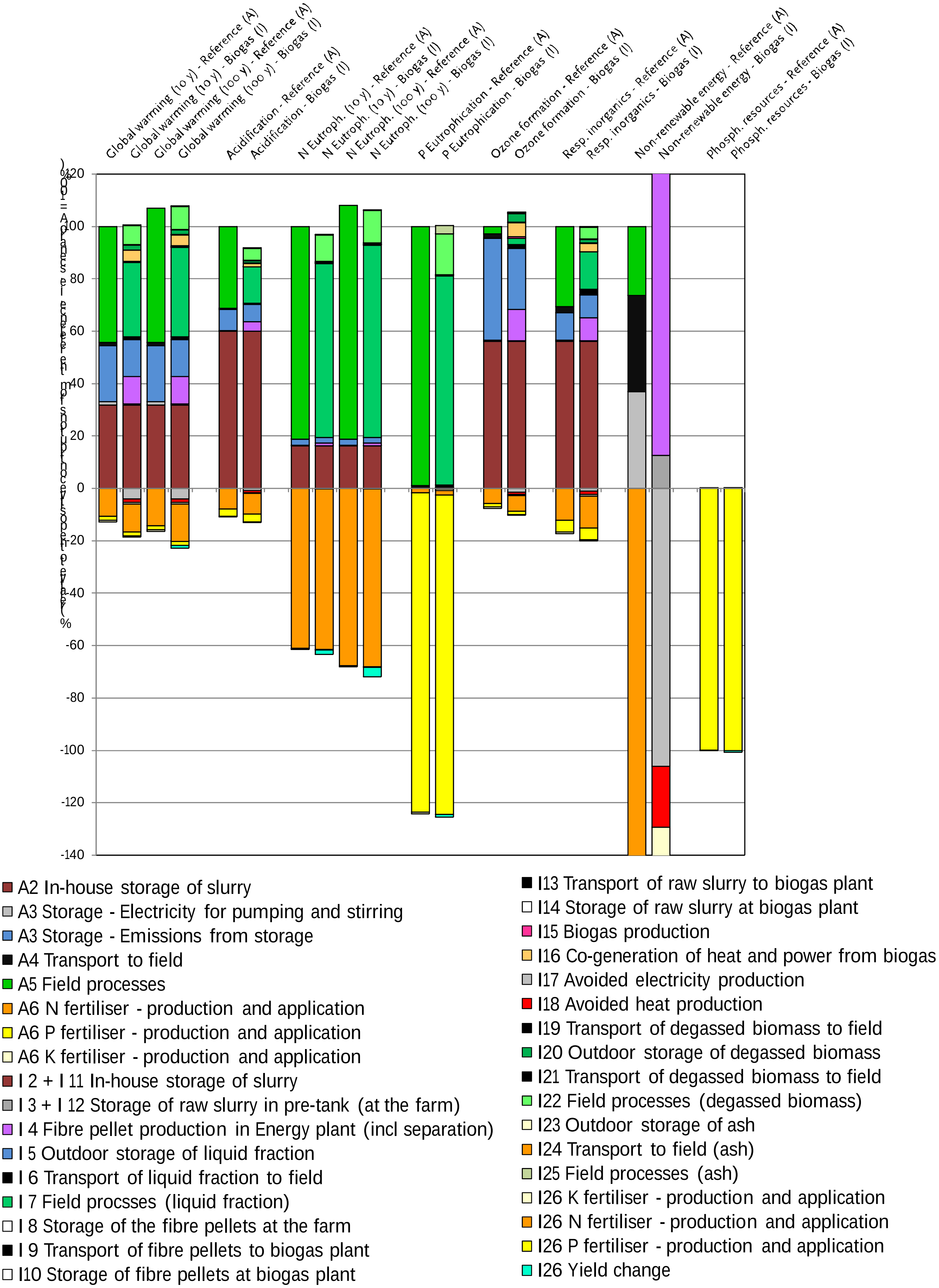
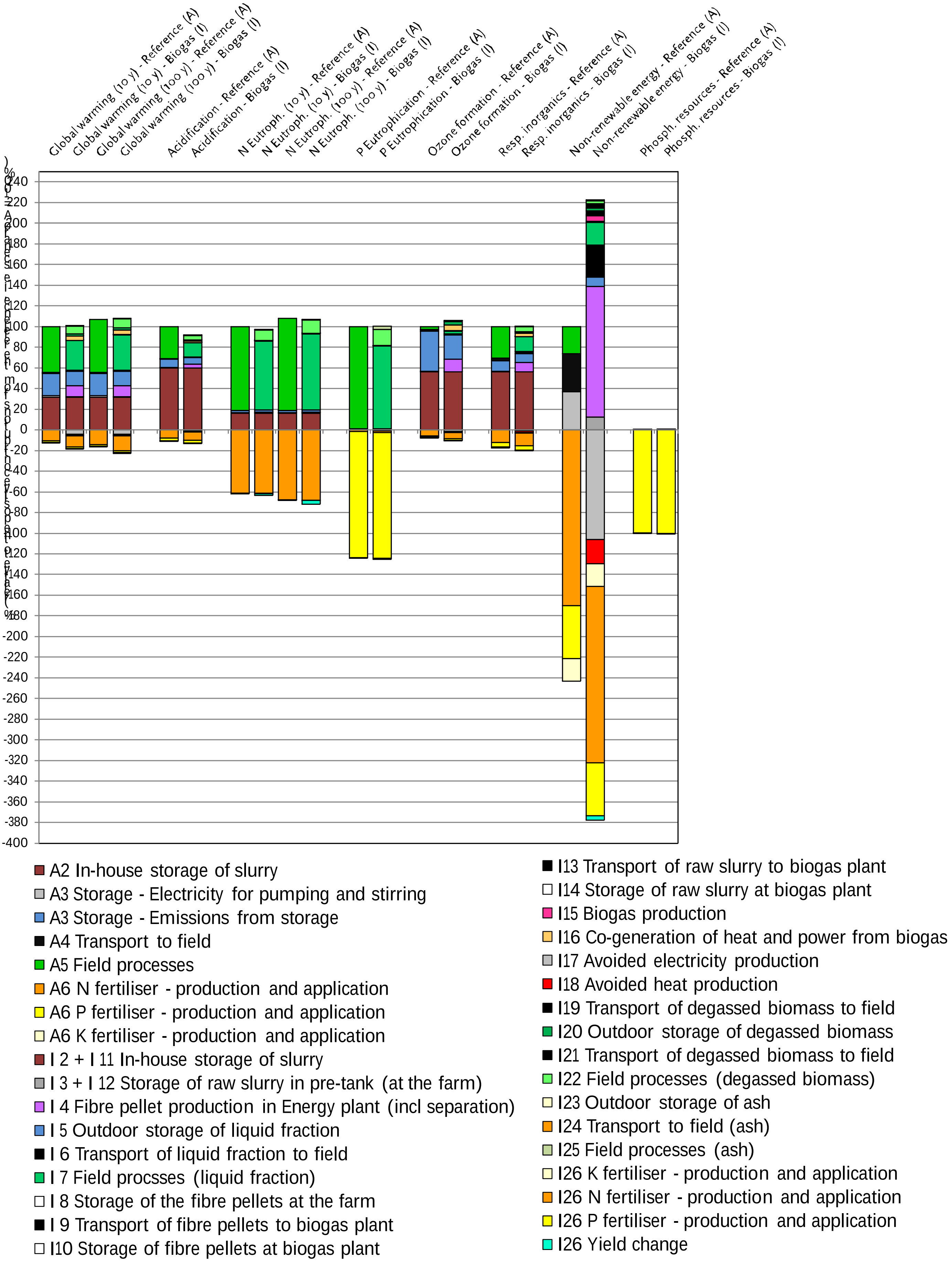


Figure 7.2.b

Overall environmental impacts for the selected environmental impacts categories – Scenario I vs Scenario A. Fattening pig slurry management. Soil type JB3. 10 and 100 years time horizon for global warming and for aquatic eutrophication (N). Axis ranging from -400 to 250.



In the following sections, the benefits (and shortcomings) of producing biogas as described in Scenario I instead of the reference slurry management are discussed in details for each impact categories.

Sensitivity analyses were performed for some processes, but are only presented using the data of Annex F, see section 8.

7.2.2 Global warming

Different trends can be observed from figure 7.2.A as regarding global warming.

First, when analysing the positive contributions, it can be seen that there are two major hot spots to global warming contribution:

- In-house storage of slurry
    - Scenario A and I: This process represents 32 % of the total positive contributions to global warming from the reference scenario.
- Field processes
    - Scenario A: This process represents 44 % of the total positive contributions to global warming from the reference scenario (and 51 % if the 100 years values are considered for C horizon in the field).
    - Scenario I: This process (for the aggregation of all organic fertilisers: liquid fraction, degassed biomass mixture and ashes) represents 36 % of the total positive contributions to global warming from the reference scenario (and 43 % if the 100 years values are considered for C horizon).

As for the other scenarios assessed, the high contribution from the in-house storage is due to CH_4 emissions. There are only three gases contributing to the global warming potential of this process: CH_4 (84 %), N_2O (12 %) and CO_2 (4 %). The proportions shown in parenthesis are for Scenario I and for the 10-years value as regarding the C horizon considered for field processes.

Important emissions from CH_4 were expected for this process, as the anaerobic conditions for slurry stored below animal floors favour CH_4 formation more than the formation of other greenhouse gases. Yet, the high absolute contribution from CH_4 is due to a potentially conservative methodological choice, as detailed in section 4.2.2.

For Scenario I, the contribution of field processes to global warming potential is dominated by biogenic CO_2 (due to C applied emitted as CO_2) (66 % of the contribution to global warming from field processes) and N_2O (31 %). The contribution to global warming from field processes caused by fossil CO_2 emissions (due to diesel combustion) is 2 %. The balance comes from a multitude of other substances, having small contributions all together.

As explained in section 4.2.2, high contributions to global warming potential from N_2O were expected for field processes, as N_2O has a 100-years global warming potential of 296 kg CO_2 equivalent per kg N_2O (based on the EDIP method, in turn based on IPCC, 2001, table 6.7). Because, for all fractions applied to field, the emission of N_2O were estimated based on the IPCC methodology (IPCC, 2006), the N_2O emissions are function of the N content in the applied slurry. This is why the liquid fraction has the highest contribution to N_2O, as it has the highest N content per functional unit. The ashes, assumed to contain no N, therefore do not contribute to generate N_2O. The contribution of N_2O to global warming from field processes is similar for Scenario A than Scenario I (32 kg CO_2 equivalent in Scenario I and 35 kg CO_2 equivalent in Scenario A). If the emissions of N_2O-N represent 3 to 5 % of the N applied as suggested by Crutzen et al. (2008) rather than the 1 % of the IPCC methodology (IPCC, 2006) as used in this study, the global warming contribution from field processes would be much more important, as a small increment of N_2O has huge impacts on global warming potential.

It shall also be emphasised that the contribution to global warming from field processes from Scenario I are below those of scenario A (table 7.2), but the difference is not as big as in the case of the other scenarios. In the present case, the difference between scenario I and A for field processes is mainly due to biogenic CO_2 emissions, which are lower for Scenario I (67.6 kg CO_2 equivalent in Scenario I as compared to 88.6 kg CO_2 equivalent in Scenario A).This reflects the fact that a share of the C is recuperated for energy production in Scenario I, thus not available for CO_2 emissions in the field.

For Scenario I, the biogenic CO_2 emissions from field processes (i.e. the portion of the C from slurry applied that is emitted as CO_2) are the highest with the application of the liquid fraction (51.5 kg CO_2equivalent) as compared to the degassed biomass mixture (16 kg CO_2equivalent). This is because the liquid fraction has the highest C content per functional unit (19.66 kg C per functional unit as compared to 5.74 kg C per functional unit for the degassed biomass mixture). This reflects the potential for improvement as regarding the separation efficiency of C in the first separation.

The co-generation of heat and power from biogas also represents, in the case of Scenario I, a positive contribution to global warming, representing 4 % of the total positive contributions to global warming from the reference scenario. This, as explained in section 4.2.2, is mainly due to the combustion gases from burning the biogas (i.e. CH_4 and CO_2) in the biogas engine.

Another interesting observation to highlight from figure 7.2.A is the benefit on global warming contribution obtained through storing the slurry as separated (and degassed) fractions rather than as raw slurry. While storage of raw slurry (Scenario A) represents 21.4 % of the total positive contributions to global warming from the reference scenario, the contribution from separated liquid is 14 %, and it is 2 % for the degassed biomass mixture. This is mainly because of lower CH_4 emissions due to the separation (and digestion) of the VS, as explained in section 4.2.2. The fact that the contributions are much lower for the degassed biomass mixture reflects that the flow of degassed biomass to store is small in the overall system (116 kg degassed biomass mixture entering the storage per functional unit, figure 7.1). In comparison, there is 843.7 kg of liquid fraction entering the storage per functional unit.

In Scenario I, another significant contributor to global warming is the production of the fibre pellets, representing 10.5 % of the total positive contributions to global warming from the reference scenario (29.9 kg CO_2 equivalent for this process, including separation). The main contributing substance for this is CO_2. This CO_2 is 56 % biogenic and 44 % fossil. The biogenic portion represents 16.10 kg CO_2 equivalent and is due to the losses of C through CO_2 during the fabrication of the pellets (this data is based on in-situ measurements). The fossil portion represents 12.48 kg CO_2 equivalent and is due to the energy consumption.

Finally, as it can be observed from figure 7.2.A, the contributions to global warming from the transportation and the biogas production itself are rather negligible.

If both slurry management assessed allow to avoid the use of inorganic fertilisers (N, P and K), the biogas scenario also allow to avoid the production of marginal heat and electricity (see definition section 2.3). Avoiding the production of marginal electricity (a mix of wind, coal and natural gas, see table 2.1) by the use of the electricity produced from the biogas allow additional benefits in terms of global warming contribution avoided. This corresponds to an “avoidance” of 4 % of the total positive contributions to global warming from the reference scenario. Avoiding the production of marginal heat (i.e. 100 % coal, see table 2.1) through the heat produced from the biogas also has a positive impact on global warming contribution (an avoidance of 1.2 % of the total positive contributions to global warming from the reference scenario).

Avoiding the production and use of inorganic fertilisers (particularly N, but also P and K to a lesser extent) through the use of the produced organic fertilisers contribute, for both Scenario A and Scenario I, to the avoidance of global warming potential, and this avoidance is in the same order of magnitude for both scenarios. Avoiding the production and use of inorganic N avoids the production of N_2O which represents the main reason for the magnitude of avoided contribution to global warming for this process. In the present case, differently from previous scenarios, the amount of avoided N differs slightly between Scenario A and Scenario I. This is because of the fact that part of the produced fibre pellets is burned in the energy plant to be used in order to cover the heat need. This burned fraction allow the use of a different substitution rule for the liquid portion associated with it, see Annex I for more details. However, this difference is so small that it does not make any major difference in the overall picture, as it can be seen from figure 7.2.A.

The amount of inorganic P and K substituted in Scenarios A and I are different, but this does not affect the avoided contribution to global warming, as they are in the same order of magnitude for both scenarios. In the case of avoided P and K, the benefits are mostly due to the avoided fossil CO_2.

Similarly, the higher wheat production obtained through higher yields in Scenario I also allows to avoid contribution to global warming (mostly through N_2O), though this is rather small.

Overall, when the “deductions” from the avoided contributions to global warming are accounted for, the difference between managing the slurry as in Scenario A and I is 15 kg CO_2 equivalent. Accounting for the uncertainties (figure 7.9.A), this benefice becomes rather small.

Table 7.2 summarises, for selected processes, the contribution of the main contributing substances to global warming, for both Scenario A and I.

Table 7.2.
Scenario I vs A: Contribution of the main contributing substances to global warming for selected processes. **All values in kg CO_2 equivalent**. Soil JB3 (sandy).[1]

Processes		CH_4	Biogenic CO_2 (field)	N_2O	CO_2 (fossil or biogenic not from field processes)	Total emission (kg CO_2 equivalent) for the process
Scenario A (pig)						
In-house storage		75.67	0	11.16	3.44	90.3
Outdoor storage		44.62	0	16.00	0.18	60.8
Field processes		0	88.62	34.87	2.29[b]	125.9[a]
Scenario I						
In-house storage		75.67	0	11.16	3.44	90.3
Outdoor storage	Liquid fraction	24.22	0	13.29	0.90[b]	40.0[a]
	Degassed biomass mixture	3.40	0	1.34	0.25[b]	5.2[a]
	Ashes	0	0	0	0	0
Field processes	Liquid fraction	0	51.50	27.43	1.93[b]	80.9[a]
	Degassed biomass mixture	0	16.07	4.60	0.27[b]	20.9[a]
	Ashes	0	0	0[c]	0[b,c]	0[c]
Biogas production		0.59	0	0.01	0.53	1.2[a]
Co-generation heat and power		0.96	0	0.01	10.78	11.9[a]
Fibre pellets production (incl. separation)		0	0	0.14	28.57[d]	29.91[a]
Avoided electricity production		0	0	-0.12	-10.51[b]	-11.6[a]
Avoided heat production		0	0	-0.01	-3.30[b]	-3.5[a]

[1] The number of digits is *not* an expression of the uncertainty.

[a] The balance is from other global warming contributing substances not presented in this table.

[b] Fossil CO_2

[c] This is not a zero value

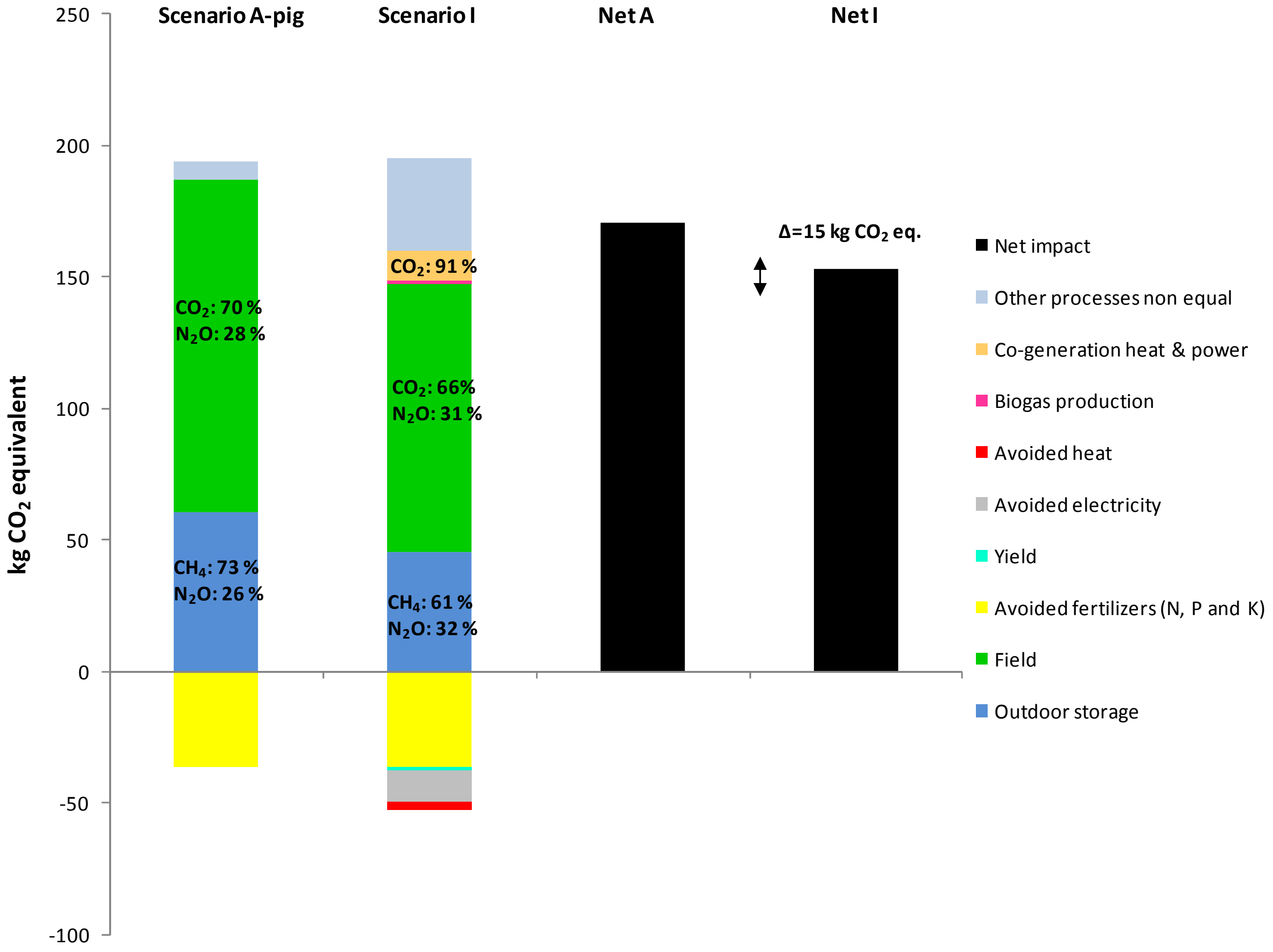
[d] This includes 16.10 kg CO_2 from biogenic origin (based on measurements) and 12.48 kg CO_2 from fossil origin (energy consumption)

The major results as regarding global warming can be summarised as:

- Overall, when accounting for uncertainties, there is a very small benefit to manage the slurry as in Scenario I, as opposed to the reference slurry management.
- There are 2 major hot spots regarding global warming:
  - In-house storage of slurry. The main contributor is CH_4.
  - Field processes. The main contributor is CO_2 due to field processes.
- Storing separated and digested slurry has benefits on global warming as compared to storage of raw slurry.
- The contribution to global warming from the fabrication of the pellets has significance in the overall picture.
- The contributions to global warming from the biogas process and the transportation are rather negligible in both scenarios.
- Both scenarios allow avoiding the contributions to global warming from the production of inorganic N, P and K fertilisers in the same magnitude.
- Scenario I allows to avoid the production of marginal heat and electricity, which has extra benefits on global warming contributions avoided. The avoided wheat induced by higher yield in Scenario I has minor importance in the overall picture.

This information is summarised in figure 7.3. This figure presents the contribution to climate change of Scenario A and I only for the processes that are not equal between A and I (i.e. in-house storage). All processes are presented; the category labelled “other processes non equal” represents the aggregation of all processes not presented in the legend.

Figure 7.3.
Comparison of Scenario I vs Scenario A for global warming including carbon sequestration, for processes differing between A and I only. Soil JB3, 10 years values.



7.2.3 Acidification

As it can be observed from figure 7.2, the major contributor to acidification is in-house storage, for both scenarios. In both cases, it represents 60 % of the total positive contributions to acidification from the reference scenario. This is mostly due to one substance, namely NH_3, as discussed in section 4.2.3.

Field processes represent the other most important contributor to acidification, representing, for Scenario I, about 20 % of the total positive contributions to acidification from the reference scenario (accounting for liquid fraction, degassed biomass mixture and ashes). The main contributing substance in this case is also NH_3 (96 % of the contributions for this process). The contribution from the liquid fraction represents 75 % of the share for the total contribution from field processes to acidification in Scenario I. This reflects the important flow of liquid fraction as compared to the flow of degassed biomass involved in the system. The overall contribution to acidification from field processes is much lower for Scenario I (15.7 m^2

unprotected ecosystem) as compared to Scenario A (9.2 m^2 unprotected ecosystem). This reflects the positive effect of the separation, where the N is most likely to enter the soil quickly due to the lower dry matter content, and thereby it reduces the potential for this N to be emitted as NH_3 in the atmosphere (see detailed explanation in Annex F, section F.7.3)

The outdoor storage, if the contributions from the liquid fraction and the degassed biomass are aggregated in the case of Scenario I, contributes to acidification in the same magnitude for both scenarios. The main contributing substance to acidification for outdoor storage is also NH_3 (77% of the contributions for this process).

The fabrication of the pellets in the energy plant also has some significance as regarding acidification in Scenario I (representing 3.5 % of the total positive contributions to acidification from the reference scenario). The main contributing substance responsible for this is NO_x (representing 81 % of the contributions to acidification for this process). The co-generation of heat and power has here a minor contribution to acidification (representing 1.3 % of the total positive contributions to acidification from the reference scenario). The main contributing substance for this process is also NO_x.

For Scenario I, as it can be observed in figure 7.2.A, the contributions to acidification from the biogas production and the transportation are rather small.

The amount of fertiliser avoided, though different, has the same magnitude for both scenarios, and so is the avoided contribution to acidification from the inorganic fertilisers not produced/used.

The production of marginal heat avoided through the use of biogas for heating has a small contribution to acidification avoidance, and the production of marginal electricity avoided as well as the wheat production avoided have even smaller contributions in avoiding acidification.

Table 7.3 summarises, for selected processes, the contribution of the main contributing substances to acidification, for both Scenario A and I.

Table 7.3.
Scenario I vs A: Contribution of the main contributing substances to acidification for selected processes. **All values in m^2 unprotected ecosystem (UES)**. Soil JB3 (sandy).[1]

Processes		NH_3	NO_X	SO_2	Total emission (m^2 UES) for the process
Scenario A (pig)					
In-house storage		29.77	0.37	0	30.14
Outdoor storage		3.09	0.93	0	4.02
Field processes		15.25	0.34	0.06	15.66[a]
Scenario I					
In-house storage		29.77	0.37	0	30.14
Outdoor storage	Liquid fraction	2.55	0.78	0.02	3.36[a]
	Degassed biomass mixture	0.42	0.08	0.01	0.51[b]
	Ashes	0	0	0	0
Field processes	Liquid fraction	6.61	0.28	0.05	6.94[b]
	Degassed biomass mixture	2.20	0.04	0.01	2.25[b]
	Ashes	0[c]	0[c]	0[c]	0[c]
Biogas production		0[c]	0.01	0.01	0.02[b]
Co-generation heat and power		0[c]	0.60	0.06	0.66[b]
Production of fibre pellets (incl separation)		0.01	1.43	0.28	1.76[a]
Avoided electricity production		0[c]	-0.10	-0.23	-0.38[b]
Avoided heat production		0[c]	-0.07	-0.32	-0.48[b]

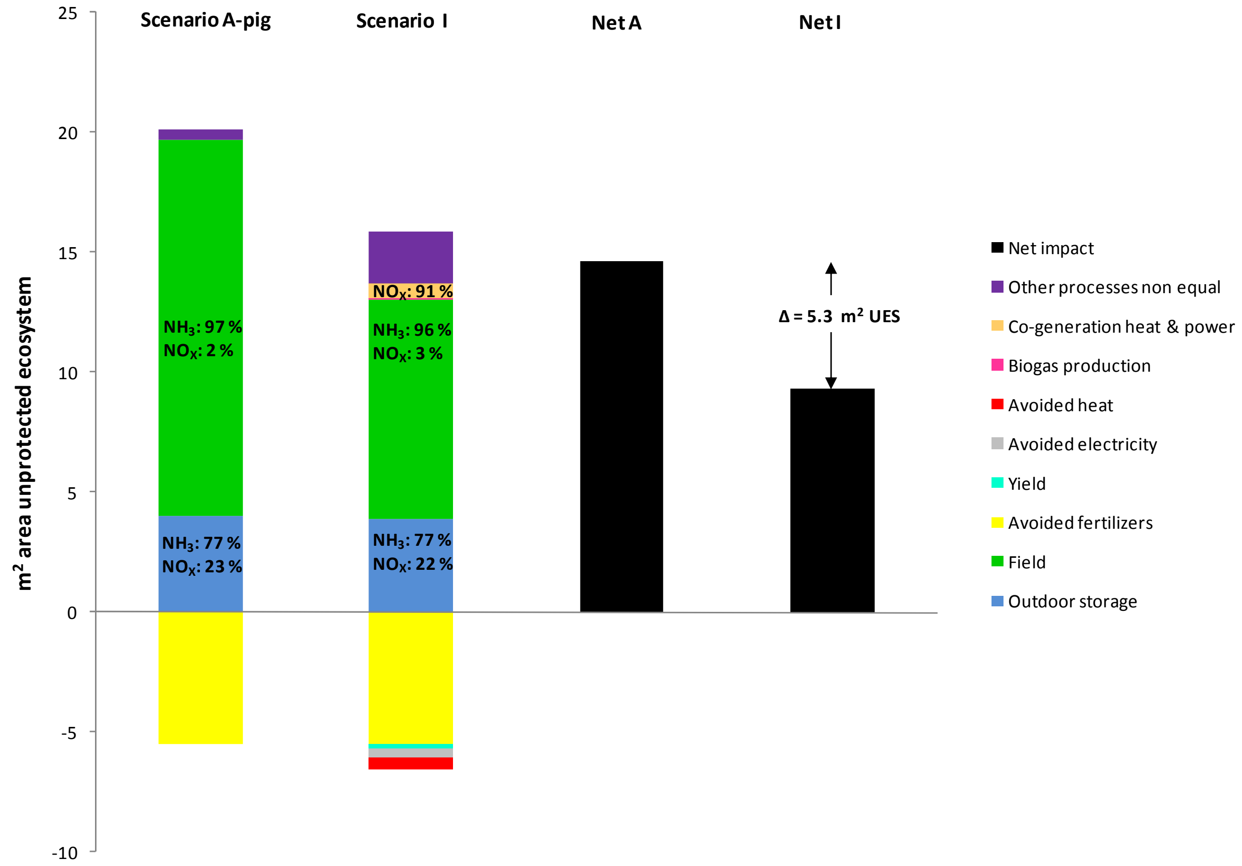
[1] The number of digits is *not* an expression of the uncertainty.
[a] The balance is from other acidification contributing substances not presented in this table.
[b] This includes other contributing substances which are not reflected when contributions are presented with 2 decimal places.
[c] This is not a zero value.

The major results as regarding acidification can be summarised as:

- Overall, managing the slurry as in Scenario I allows a difference between Scenario I and A as regarding acidification but this is compensated for when taking uncertainties into account.
- There are 2 major hot spots are regarding acidification:
    - In-house storage of slurry. The main contributor is NH_3.
    - Field processes. The main contributor is NH_3.
- The overall contribution to acidification from outdoor slurry storage is similar for both Scenario A and I, and NH_3 is the main contributor.
- Acidification for field processes is less important for Scenario I as compared to the reference scenario.
- The fabrication process of the pellets also has some importance regarding its contribution to acidification.

This information is summarised in figure 7.4. This figure presents the contribution to acidification of Scenarios A and I only for the processes that are not equal between A and H (i.e. in-house storage). All processes are presented; the category labelled “other processes non equal” represents the aggregation of all processes not presented in the legend.

Figure 7.4.
Comparison of Scenario I vs Scenario A for acidification, for processes differing between A and I only. Soil JB3, 10 years values.



7.2.4 Aquatic eutrophication (N)

Aquatic N eutrophication is, as illustrated in figure 7.2.A, mostly due to field processes:

- For Scenario A, this represents 81 % of the total positive contributions to N-eutrophication from the reference scenario;
- For Scenario I, this represents 77 % of the total positive contributions to N-eutrophication from the reference scenario;

The percentages above considers 10 years value as regarding the horizon for C during field processes, these percentages are higher if 100 years values are considered, as presented in table 7.1.

The contribution to N-eutrophication from field processes is therefore similar for both scenarios. In both cases, it is essentially caused by N leaching through soils.

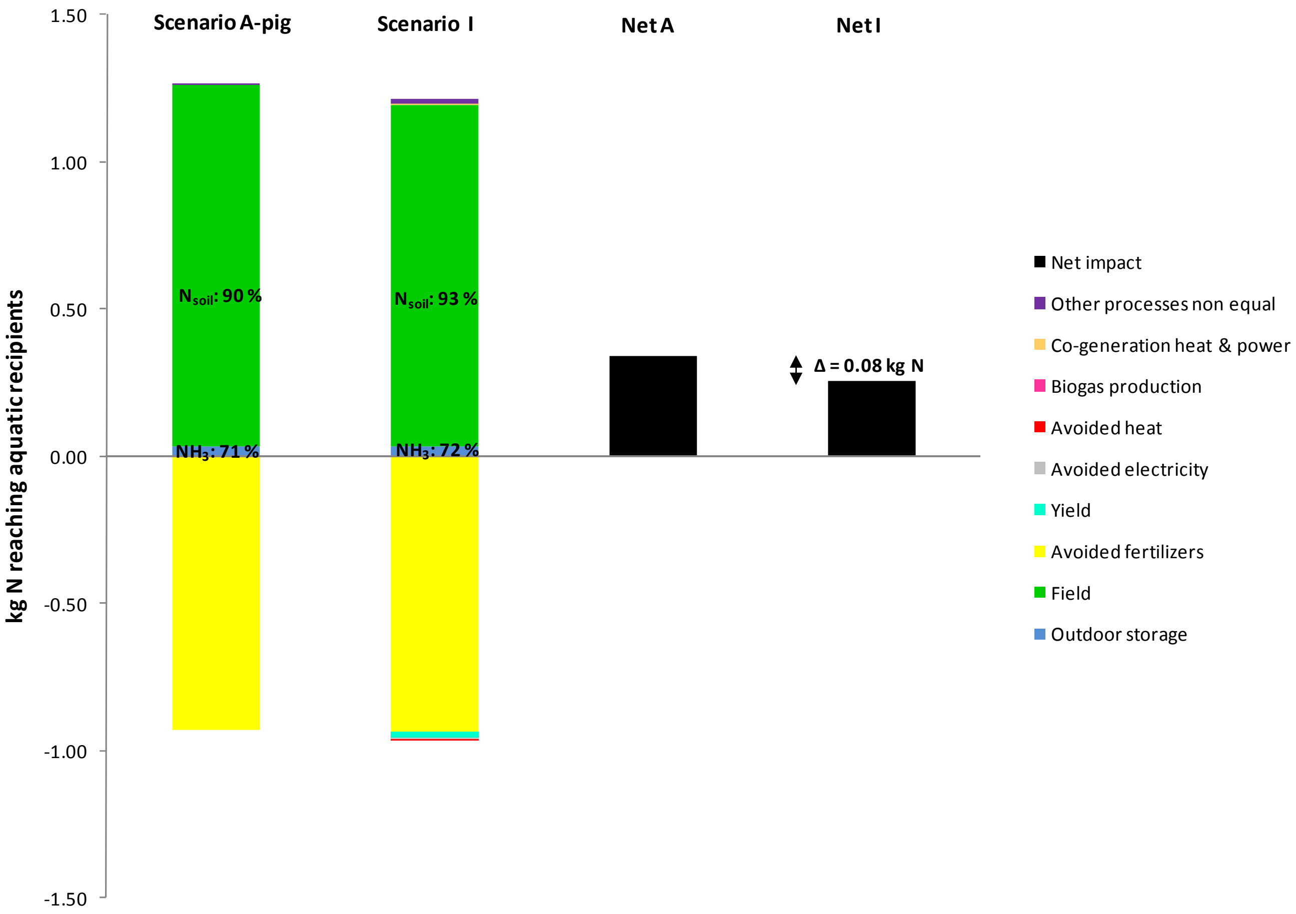
The other important contributor to N eutrophication is, for both scenarios, in-house storage, through NH_3 emissions.

In both scenarios, avoiding inorganic fertilisers to be used (mostly N) allow to avoid considerable contribution to N-eutrophication, and this is in similar magnitude for both scenarios. The wheat avoided through higher yields in Scenario I is an extra avoided contribution, but it is rather smaller in the overall picture. When the 100 years values are taken into account as regarding the horizon time for C during field processes, the gain created by avoided wheat in Scenario I becomes more significant.

Overall, when the “deductions” from the avoided contributions to N-eutrophication are accounted for, managing the slurry as described in Scenario I allows a net difference of 0.08 kg N reaching aquatic recipients (characterisation unit for N-eutrophication potential) as compared to the reference scenario. This is for the 10 years value for C. Taking the 100 years values for C during field processes into account, the difference is 0.09 kg N. However, when accounting for uncertainties, it does not appear so clear whether there is a net benefit or not (figure 7.9.A).

This information is summarised in figure 7.5. This figure presents the contribution to N-eutrophication of Scenarios A and I only for the processes that are not equal between A and I (i.e. in-house storage). All processes are presented; the category labelled “other processes non equal” represents the aggregation of all processes not presented in the legend.

Figure 7.5.
Comparison of Scenario I vs Scenario A for N-eutrophication, for processes differing between A and I only. Soil JB3, 10 years values.



7.2.5 Aquatic eutrophication (P)

As it can be observed from figure 7.2.A and table 7.1, the contribution (positive and negative) to P-eutrophication are about the same for both scenarios.

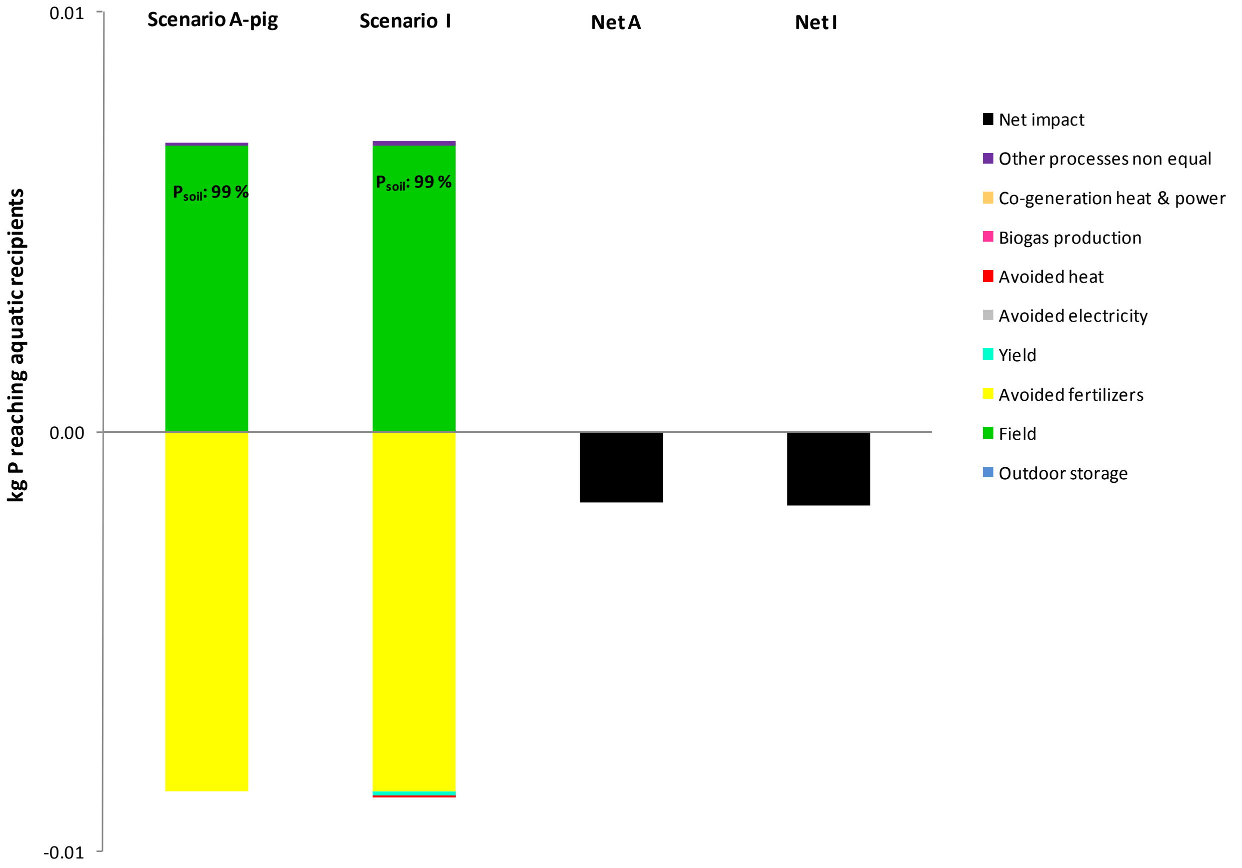
The major positive contribution to this impact is field processes (through P leaching in soils which represents 99 % of the contributions from this process in both scenarios) and the major negative contribution is the inorganic P fertiliser avoided.

For Scenario I, it can be highlighted that, for the field processes, the liquid fraction contribute to about 81 % of the total positive contributions to eutrophication (P) from the reference scenario, while it is 16 % for the degassed biomass mixture and 3 % for the ashes. This difference reflects the important difference between the mass flow of these 3 fractions in the system; while there is 916.3 kg liquid fraction ex-storage (including water) per 1000 kg slurry ex-animal, there is only 125.9 kg degassed biomass ex-storage (including water) per 1000 kg slurry ex-animal and 1.5 kg of ashes per 1000 kg slurry ex-animal.

For both fractions, it was considered that P leaching to soils corresponds to 10 % of the P applied to field, and 6 % of this has the possibility to reach aquatic recipients (based on Hauschild and Potting, 2005). This is detailed in sections I.7 and I.22 of Annex H. This assumption involves some uncertainties, as discussed in section 4.2.5.

Overall, when the “deductions” from the avoided contributions to P-eutrophication are accounted for, managing the slurry as described in Scenario I does not allow a significant benefit for P-eutrophication over managing the slurry as in the reference scenario. This is illustrated in figure 7.6.

Figure 7.6.
Comparison of Scenario I vs Scenario A for P-eutrophication, for processes differing between A and I only. Soil JB3, 10 years values.



7.2.6 Photochemical ozone formation ("smog")

In both scenarios, there are 2 main hot spots for photochemical ozone formation:

- In-house storage, representing about 56 % of the total positive contributions to photochemical ozone from the reference scenario (for both Scenario A and I).
- Outdoor slurry storage:
  - Scenario A: this process represents 39 % of the positive contributions from the reference scenario;
  - Scenario I: this process represents 26 % of the positive contributions from the reference scenario.

In the case of in-house storage, the main contributor is CH_4, which represents about 95 % of the contribution to ozone formation for this process. Concerns regarding potential overestimation of in-house CH_4 are discussed in section 4.2.6 and 4.2.2.

Methane is also the main contributing substance to ozone formation for the outdoor slurry storage process (81 % in the case of Scenario A and 74 % in the case of Scenario I). The fact that the overall contribution from outdoor storage is lower for Scenario I reflects the effect of the digestion. This is due to the lower VS content of degassed slurry, thus involving a much lower potential for CH_4 emissions. This again highlights the positive effect of slurry digestion as regarding CH_4 emissions during slurry storage.

Another contributing process to this impact category is, for Scenario I, the co-generation of heat and power. The main contributing substance in this case is NO_x (85 % of the total contributions for this process), which is emitted during the combustion of the biogas in the biogas engine.

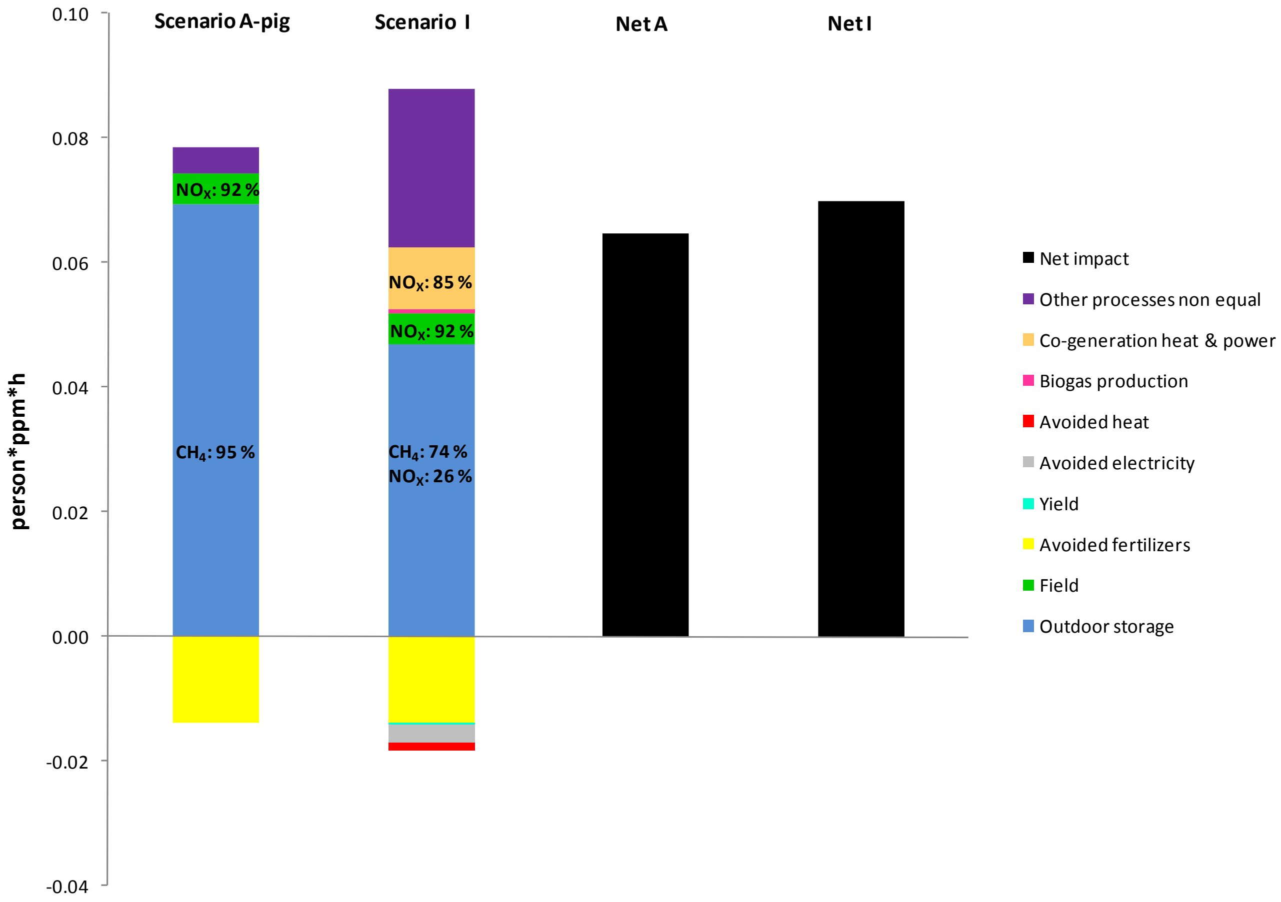
The fabrication of the pellets also contributes importantly to the photochemical ozone formation (representing about 12 % of the total positive contributions to photochemical ozone from the reference scenario). The main contributing substance in this case is also NO_x.

Avoiding marginal heat and electricity to be produced only have, for the compared scenarios, a minor contribution in avoiding the photochemical ozone formation. Avoiding inorganic fertilisers to be used/produced does contribute in reducing the overall ozone formation impact, in similar magnitude for both scenarios.

Overall, when the "deductions" from the avoided contributions photochemical ozone formation are accounted for, managing the slurry as described in Scenario I does not allow a benefit as compared to the reference slurry management.

This information is summarised in figure 7.7. This figure presents the contribution to photochemical ozone formation of Scenarios A and I only for the processes that are not equal between A and H (i.e. in-house storage not included). All processes are presented; the category labelled "other processes non equal" represents the aggregation of all processes not presented in the legend.

Figure 7.7.
Comparison of Scenario I vs Scenario A for photochemical ozone formation, for processes differing between A and I only. Soil JB3, 10 years values.



7.2.7 Respiratory inorganics (small particles)

Respiratory inorganics is caused by 3 main processes:

- In-house storage of slurry: this process represents 56 % of the total positive contributions to respiratory inorganics from the reference scenario (for both Scenario A and I).
- Field processes:
    - Scenario A: this process represents 30 % of the total positive contributions to respiratory inorganics from the reference scenario
    - Scenario I: this process represents about 19 % of the total positive contributions to respiratory inorganics from the reference scenario
- Outdoor slurry storage:
    - Scenario A and I: this process represents about 10 % of the total positive contributions to respiratory inorganics from the reference scenario

For in-house storage, the main contributor is NH_3 emissions, representing about 97 % of the contribution to respiratory inorganics for this process.

For field process, the main contributing substance to respiratory inorganics is also NH_3 (contributing to about 91 % in Scenario A and 876% in Scenario I for this process).

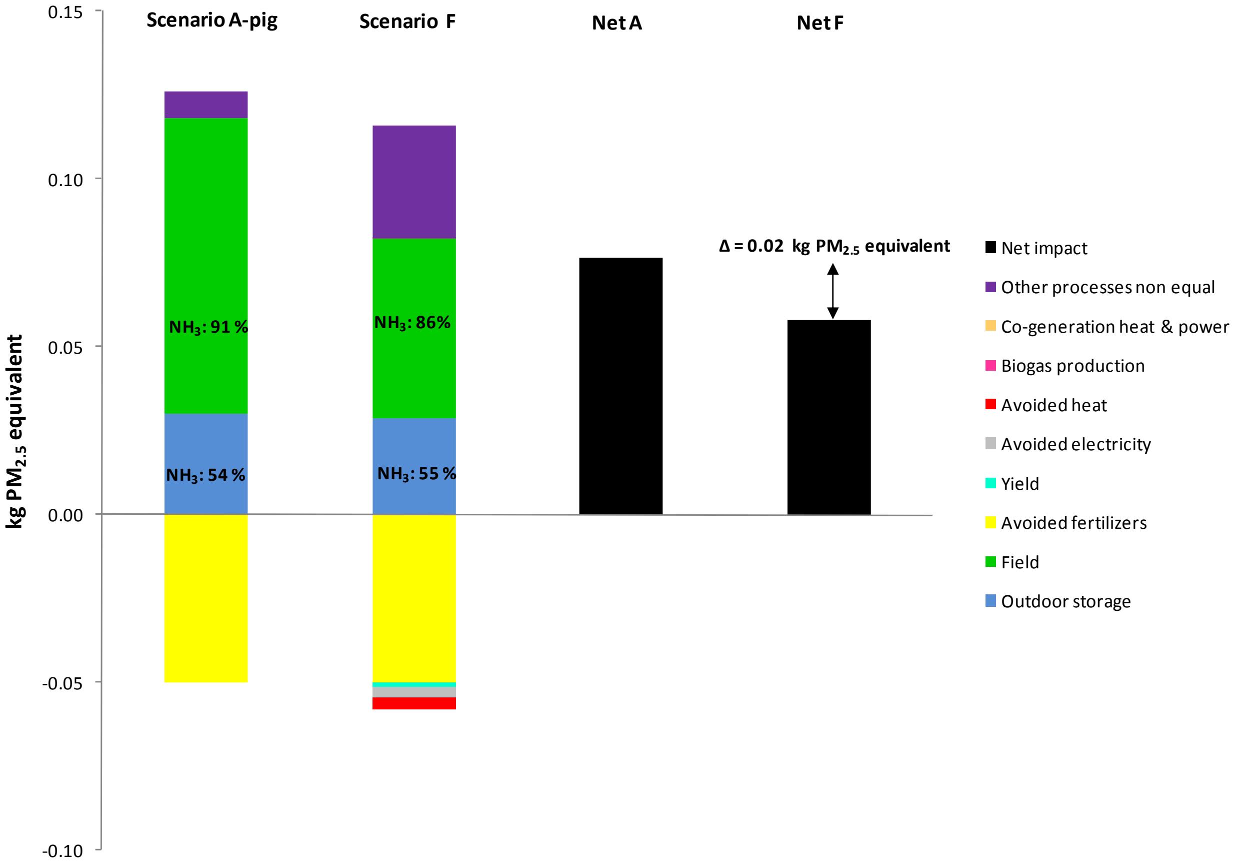
For outdoor storage, the contributions are divided between NH_3 and NO_x. In the case of Scenario I, the fabrication of the fibre pellets, also contributes to "respiratory inorganics" formation, representing 9 % of the total positive contributions to respiratory inorganics from the reference scenario. The main contributing substance in this case is NO_x.

Avoiding marginal heat and electricity to be produced only have a minor contribution in avoiding respiratory inorganics. This observation also applies for the avoided wheat production induced by the extra yield. Avoiding inorganics fertilisers to be produced does contribute to avoid "respiratory inorganics" formation, in similar magnitude for both scenarios.

Overall, when the "deductions" from the avoided contributions to "respiratory inorganics" are accounted for, managing the slurry as described in Scenario I allows a net difference of 0.018 kg $PM_{2.5}$ equivalent as compared to the reference scenario. This is not significant when uncertainty is accounted for (figure 7.9.A).

This information is summarised in figure 7.8. This figure presents the contribution to "respiratory inorganics" of Scenarios A and I only for the processes that are not equal between A and I (i.e. in-house storage is not included). All processes are presented; the category labelled "other processes non equal" represents the aggregation of all processes not presented in the legend.

Figure 7.8.
Comparison of Scenario I vs Scenario A for "respiratory inorganics", for processes differing between A and I only. Soil JB3, 10 years values.



7.2.8 Non-renewable energy resources

Both scenarios contribute to the use of the non-renewable energy through the use of marginal electricity, of liquid fuel for transportation (road and tractors) and the use of marginal heat. This is reflected in figure 7.2.B where the contributing processes are those requiring electricity or fuel inputs. The importance of the process “production of fibre pellets” for this impact category is highlighted in figure 7.2.B.

Avoiding marginal electricity but also heat to be produced through the use of biogas for scenario I allows a considerable “avoidance” of non-renewable energy to be used. This is also true for the fertilisers avoided, but the magnitude of this is similar for both scenarios. The wheat production avoided in Scenario I through the yield increase also contributes to avoid, in a rather small magnitude, the use of non-renewable energy resources.

Overall, the difference between Scenario I and the reference scenario lies mostly in the avoided contributions rather than in the positive contributions. This is why, as explained in section 4.2.8, using less electricity or heat input for the biogas process (as suggested in Annex F, section F.15.3) would not contribute to a drastic change of the situation for this impact category, given the larger importance of the avoided contributions.

Overall, when the “deductions” from the avoided contributions to non-renewable energy use are accounted for, the difference between managing the slurry as described in Scenario I as compared to the reference slurry management is 19 MJ of (primary) non-renewable energy. This however becomes lower when taking the uncertainties into account (figure 7.9.B).

7.2.9 Consumption of phosphorus as a resource

Both scenarios allows about the same amount of P to be preserved as a resource (through the avoidance of inorganic P fertiliser to be produced). The wheat production avoided in Scenario I (induced by the increased yield) is an extra as compared to the reference scenario but has a rather insignificant contribution in P consumption avoidance, as it can be seen it table 7.1 and figure 7.2.A.

7.2.10 Carbon stored in soils

Through Scenario I, a certain amount of C ends up to be stored in soils, which means this C is not emitted as CO_2. This is through the C of the different slurry fractions that is applied to field and not emitted as CO_2.

For the reference scenario, a total of 3.61 kg C per 1000 kg pig slurry ex-animal is stored in soils, corresponding to 13.2 kg CO_2 not emitted per functional unit. This is for a C horizon in the field of 10 years. With the 100 years values, more CO_2 is emitted and consequently less C is stored per functional unit (1.03 kg), resulting to 3.8 kg CO_2 not emitted per 1000 kg pig slurry ex-animal. These values are presented in table 4.1 of Wesnæs et al. (2009).

For Scenario I, less C is added to field per functional unit but also less CO_2 is overall emitted (table 7.2). As a result, the amount of C sequestrated in the soil per functional unit (2.99 kg C considering 10 years values; 0.51 kg C considering 100 years values) is similar, though lower than the amount of C sequestrated for the reference scenario. In terms of CO_2 avoided, this correspond to 10.9 kg CO_2 (10 years values) and 1.9 kg CO_2 (100 years values) per 1000 kg pig slurry ex-animal.

7.3 Uncertainties

The uncertainties on the compared results have been estimated by analysing the most important factors that are ***changed***, when comparing scenario I with the reference scenario A. It means that the uncertainties for each scenario is not analysed as such, but only the emissions that are important for the ***differences***. The uncertainties on the comparisons are based on estimates of the uncertainties on those emissions that are most important for the changes.

The uncertainties are related to the total positive contributions from the reference scenario A (i.e. the total that is set to 100% in figures 7.9 and 7.10 as “index”).

The values of the uncertainty ranges are shown in table 7.4.

7.4 Synthesis of the results for all impact categories assessed

Table 7.4 compares the overall characterised results of Scenario A versus Scenario I, for all impacts categories (including carbon stored in soils). It also presents the uncertainty ranges for all impact category results.

Figures 7.9.A and 7.9.B illustrate the results presented in table 7.4, and give an impression of the uncertainty. The difference between these two figures is the x axis, which has a greater range in the case of figure 7.9.B in order to capture the whole impacts of non-renewable energy consumption. Figures 7.10.A presents only the net differences between Scenario A and I, including the uncertainties.

Table 7.4.
Comparison of the impacts from Scenario A (reference) versus Scenario I (biogas from raw pig slurry + fibre pellets). The number of digits is *not* an expression of the uncertainty.

Impact category	Scenario A - pig	Scenario I	Difference, i.e. Biogas scenario I minus Reference scenario A	Conclusion
Global warming (during 10 years) [kg CO$_2$ eq.]				
Positive contributions:	+284 kg	+ 285 kg	-15 [-23 to -8] kg CO$_2$ eq.	3-8% reduction of positive contributions from scenario A
Negative contributions:	- 36 kg	- 53 kg		
Net:	= 248 kg	= 233 kg		
Global warming (during 100 years) [kg CO$_2$ eq.]				
Positive contributions:	+ 304 kg	+ 306 kg	-16 [-24 to -8] kg CO$_2$ eq.	3-8% reduction of positive contributions from scenario A
Negative contributions:	- 47 kg	- 65 kg		
Net:	= 257 kg	= 241 kg		
Acidification [m^2 UES, i.e. area of unprotected ecosystem]				
Positive contributions:	+ 50.3 m^2	+ 46.0 m2	-5.3 [-13 to +3] m^2 UES	No significant difference due to uncertainties
Negative contributions:	-5.5 m^2	-6.5 m2		
Net:	= 44.8 m^2	= 39.5 m2		
N-eutrophication (aquatic) (during 10 years) [kg N - amount reaching aquatic recipients]				
Positive contributions:	+ 1.51 kg	+ 1.46 kg	-0.08 [-0.25 to +0.08] kg N	No significant difference due to uncertainties
Negative contributions:	- 0.93 kg	- 0.96 kg		
Net:	= 0.59 kg	= 0.50 kg		
N-eutrophication (aquatic) (during 100 years) [kg N - amount reaching aquatic recipients]				
Positive contributions:	+ 1.63 kg	+ 1.61 kg	-0.09 [-0.28 to +0.09] kg N	No significant difference due to uncertainties
Negative contributions:	- 1.03 kg	- 1.09 kg		
Net:	= 0.61 kg	= 0.52 kg		
P-eutrophication (aquatic) [kg P - amount reaching aquatic recipients]				
Positive contributions:	+ 0.0069 kg	+ 0.0069 kg	-0.00007 [-0.0002 to 0.0001] kg P	No significant difference due to uncertainties
Negative contributions:	- 0.0086 kg	- 0.0087 kg		
Net:	= -0.0017 kg	= -0.0017 kg		
Photochemical ozone formation [person.ppm.hr - see section 3.4.7]				
Positive contributions:	+ 0.179 p.p.h	+ 0.19 p.p.h	+0.005 [-0.005 to +0.015] p.p.h	No significant difference due to uncertainties
Negative contributions:	- 0.014 p.p.h	-0.02 p.p.h		
Net:	= 0.17 p.p.h	= 0.17 p.p.h		
Respiratory Inorganics [kg PM2.5 eq, i.e. kg equivalents of 2.5 µm size particles]				
Positive contributions:	+ 0.29 kg	+ 0.29 kg	-0.009 [-0.028 to +0.009] kg PM2.5	No significant difference due to uncertainties
Negative contributions:	- 0.05 kg	- 0.06 kg		
Net:	= 0.24 kg	= 0.23 kg		
Non-renewable energy [MJ primary energy]				
Positive contributions:	+ 151 MJ	+ 336 MJ	-19 [-13 to -24] MJ	8-16% reduction of positive contributions from scenario A
Negative contributions:	-369 MJ	-572 MJ		
Net:	= -217 MJ	= -236 MJ		
Phosphorus Resources [kg P]				
Positive contributions:	0 kg	+ 0 kg	-0.01 [-0.017 to 0) kg P	No significant difference due to uncertainties
Negative contributions:	- 1.34 kg	- 1.35 kg		
Net:	= -1.34 kg	= -1.35 kg		
Carbon stored in soil during 10 years [kg C] **and corresponding amount of CO$_2$-eq**				
C added with slurry:	+ 31.7 kg C	+ 25.4 kg C	-0.63 [-1.7 to +0.5] kg C -2.3 [-6.3 to +1.7] kg CO2	No significant difference due to uncertainties
C lost as CO2:	-28.1 kg C	- 22.4 kg C		
C stored in soil:	= 3.6 kg C	= 3.0 kg C		
Net CO2:	= 13.2 kg CO$_2$	= 10.9 kg CO$_2$		
Carbon stored in soil during 100 years [kg C] **and corresponding amount of CO$_2$-eq**				
C added with slurry:	+ 31.7 kg C	+ 25.4 kg C	-0.52 [-0.9 to +0.2] kg C -1.9 [-3.2 to +0.8] kg CO2	No significant difference due to uncertainties
C lost as CO2:	-30.7 kg C	- 24.9 kg C		
C stored in soil:	= 1.0 kg C	= 0.5 kg C		
Net CO2:	= 3.8 kg CO$_2$	= 1.9 kg CO$_2$		

Note: All numbers are all rounded and accordingly, if the reader calculates the difference, it might vary slightly from the numbers shown in the table.

Figure 7.9.A
Comparison of the environmental impacts from Scenario A (reference) versus Scenario I (biogas from raw pig slurry + fibre pellets). Axis ranging from -180 to 120.

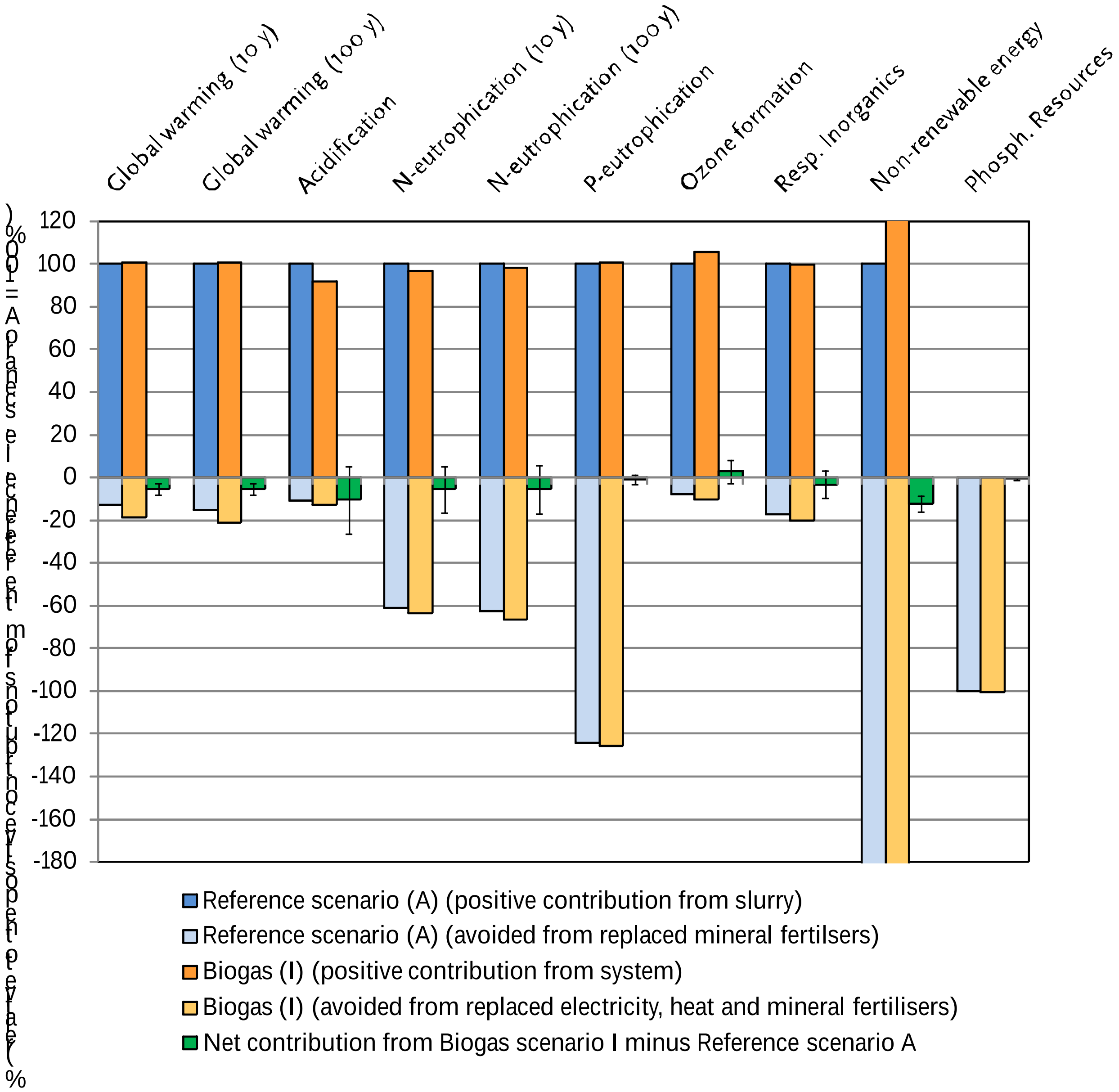


Figure 7.9.B
Comparison of the environmental impacts from Scenario A (reference) versus Scenario I (biogas from raw pig slurry + fibre pellets). Axis ranging from -1000 to 250.

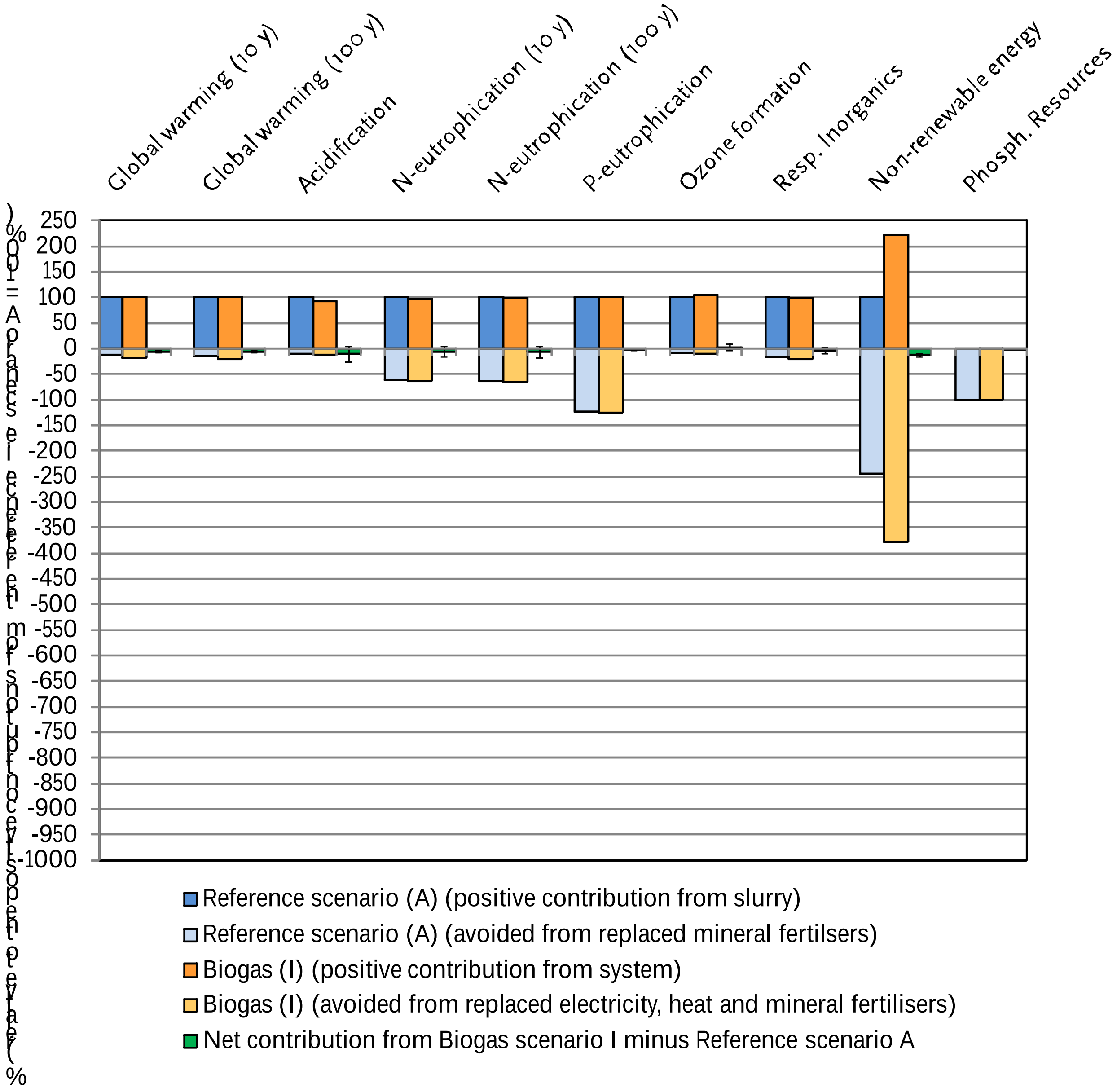
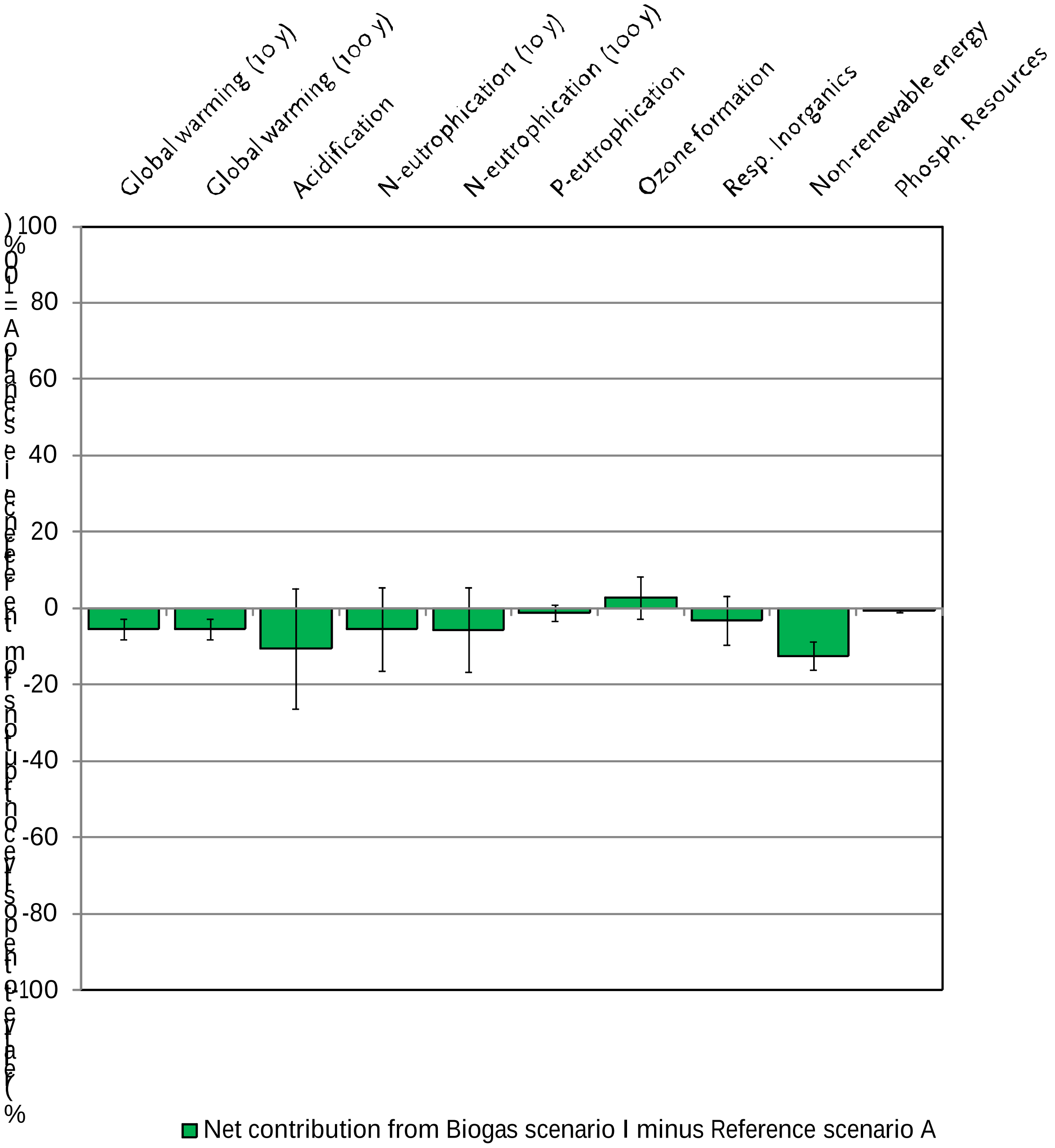


Figure 7.10.A
Comparison of the environmental impacts from Scenario A (reference) versus Scenario I (biogas from raw pig slurry + fibre pellets). Net difference only. Axis ranging from -100 to 100.



8 Sensitivity analysis

8.1 Overview of sensitivity analysis performed

While building the life cycle inventory for this study (Annexes F to I), the uncertainty regarding the choice of some values and methodologies has been highlighted. Different values or methodologies could have been used and this would have affected the outcome.

A sensitivity analysis consists to answer such “what if” questions by changing some of the inputs in the model and assess the effect this has on the overall results.

In this study, different sensitivity analyses have been performed, as enumerated through the inventory annexes. The sensitivity analyses performed are summarised in table 8.1. As it can be seen in table 8.1, most of these sensitivity analyses refer to parameters that are common for all Scenarios. In such a case, the sensitivity analysis was only performed for one scenario.

Table 8.1.
Summary of sensitivity analysis performed for the 4 biogas scenarios assessed

Parameter on which a sensitivity analysis is performed	Description of the parameter		Annexes concerned	Annex for which the sensitivity analysis is performed
	Used in this study	Alternative for sensitivity analysis		
Soil type	JB3 (sandy)	JB6 (clay)	F, G, H, I	F
Horizon for C in the field[a]	10 years	100 years	F, G, H, I	F, G, H, I
Electricity avoided from biogas production	Mix marginal (see table 2.1)	• 100 % coal • 100 % natural gas	F, G, H, I	F
Heat avoided from biogas production	Heat from coal	Heat from natural gas	F, G, H, I	F
Biogas utilisation	Used for co-generation of heat and power	Injected in the natural gas grid. It is considered that 100 % biogas = 100 % natural gas replaced, which is a rather rough assumption.	F, G, H, I	F
Heat from biogas: Amount of heat that is “usable” (i.e. not lost)	Only 60 % of the heat surpluses can be used	It is impossible to use the heat surpluses, so no heat surpluses can be used to fulfil a heat demand.	F, G, H, I	F
Long term CO2 emissions from anaerobic digestion residues	Modelled as for untreated slurry	Higher retention time	F, G, H, I	Discussion
Avoided N: N substitution values	Based on rule a) and b), see section F.28.2 of Annex F	Based on rule c), see section F.28.2 of Annex F	F, G, H, I	F

[a] This is already included in all scenarios

8.2 Results of the sensitivity analysis

8.2.1 Soil type

Figure 8.1 presents the sensitivity analysis for the different soil types. As it can be seen from figure 8.1, the soil type only affects two impact categories;

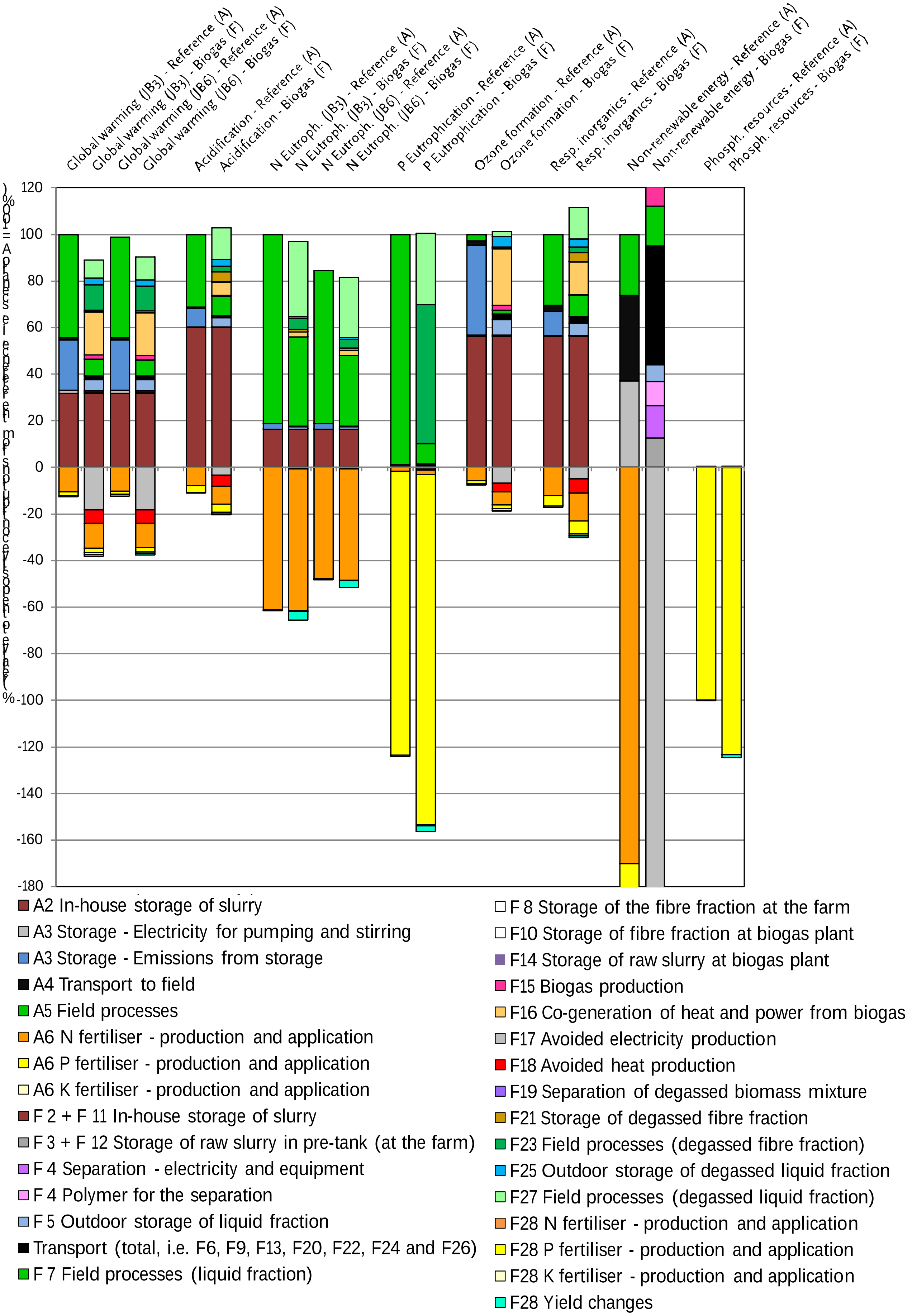
- Global warming
- N eutrophication

For this reason, a larger scale presenting the whole impact range for “non-renewable energy” is not presented as this is not affected by the soil type.

The difference between soil type JB3 and JB6 has significance for the actual value of the result, especially regarding nitrogen eutrophication (caused by N leaching). However, the goal of this study is to compare the “biogas scenario” with the reference scenario (the soil type being fixed and the same in both scenarios), and on that perspective, the differences between a given biogas scenario and the reference scenario are not changed if the soil type is changed.

Figure 8.1 is for Scenario F. The calculations and graphs have also been made for scenario G, but as these provided no additional information, they have not been shown in this report.

Figure 8.1
Sensitivity analyses, illustrating the difference between soil type JB3 and JB6
Overall environmental impacts for the selected impact categories – scenario F vs scenario A.
Fattening pig slurry management. 10 years time horizon for global warming and for aquatic eutrophication (N).



8.2.2 Horizon considered for C during field processes

In all scenarios, the impacts affected by different horizon for C during field processes, namely global warming and N-eutrophication, were presented for both 10 year and 100 year horizon values, see figures 4.2, 5.2, 6.2 and 7.2. The concept of 10 year horizon and 100 year horizon regards the time for the turnover of C and N in the field, i.e. “after 10 years, how much of the carbon has been transformed into CO_2 and how much of the nitrogen has leached” and the same after 100 years at the field.

As can be seen from figures 4.2, 5.2, 6.2 and 7.2, the time perspective has influence on the actual results for each scenario, but for the comparison between the biogas scenario and the reference scenario, the time horizon does not change the overall conclusions. The contributions to global warming (CO_2 emissions from the field) and the nitrogen leaching is higher over a 100 years perspective – but the relative difference between the biogas scenarios and the reference scenario is at the same magnitude, and most important: The conclusion does not change whether a 10 years or 100 years perspective is taken into account.

8.2.3 Electricity, heat and biogas utilisation

Figures 8.2.A and 8.2.B present the sensitivity analysis for the following possibilities for scenario F:

- Sensitivity 1: Avoided electricity is 100 % coal;
- Sensitivity 2: Avoided electricity is 100 % natural gas;
- Sensitivity 3: Avoided heat is 100 % natural gas;
- Sensitivity 4: Biogas is injected in the natural gas grid, and accordingly allow to avoid a corresponding amount of natural gas with regard to the same amount of energy content (it is assumed that 1 MJ energy content in the biogas replace 1 MJ as natural gas);
- Sensitivity 5: No avoided heat from biogas (for biogas plants situated in remote areas it might not be possible to utilise the heat for district heating and accordingly, the heat might just be wasted).

From figures 8.2.A and 8.2.B it can be seen that:

- The choice of which electricity production (sensitivity 1 and 2) that is avoided when production heat and power from biogas changes the contribution to almost all impact categories, but the overall conclusions are not changed. The sensitivity analysis with 100% coal gives the largest reductions when comparing the biogas scenarios with the reference scenarios.
- Changing the source for “avoided heat” (sensitivity 3) does not have significant influence on the overall results
- The possibility of injecting biogas directly into the natural grid (a future possibility, which requires some treatment of the biogas) in sensitivity 4 does change the overall conclusions somewhat, as no electricity production is avoided which is especially significant for the contributions to global warming and the consumption of non-renewable resources. Furthermore, in this sensitivity analysis, it is assumed that the biogas plant then have to buy natural gas to for the heating requirements at the biogas plant (in the biogas scenarios this heat is taken from the heat produced from the biogas and is in this way “free”). It should be noted that if this possibility is seriously

considered – to inject biogas directly into the natural gas grid – a more thorough Life Cycle Assessment is required in order to investigate the consequences of this. This sensitivity analysis only provides a very rough estimate.

- In sensitivity analysis 5, the heat produced by the biogas plant is not utilised. As can be seen from figures 8.2.A and 8.2.B this has influence on all impact categories, especially on global warming and consumption of non-renewable resources. The reductions gets smaller, however, the conclusion remains: The biogas production reduces the contributions to global warming and the savings of non-renewable resources.

The calculations and graphs have also been made for scenario G, but as these provided no additional information, they have not been shown in this report.

Figure 8.2.a
Sensitivity analysis: avoided heat and electricity, biogas utilisation and amount of usable heat. Scenario F vs scenario A. Fattening pig slurry management. Soil type JB3. 10 years time horizon for global warming and for aquatic eutrophication (N). **Axis ranging from -180 to 120.**

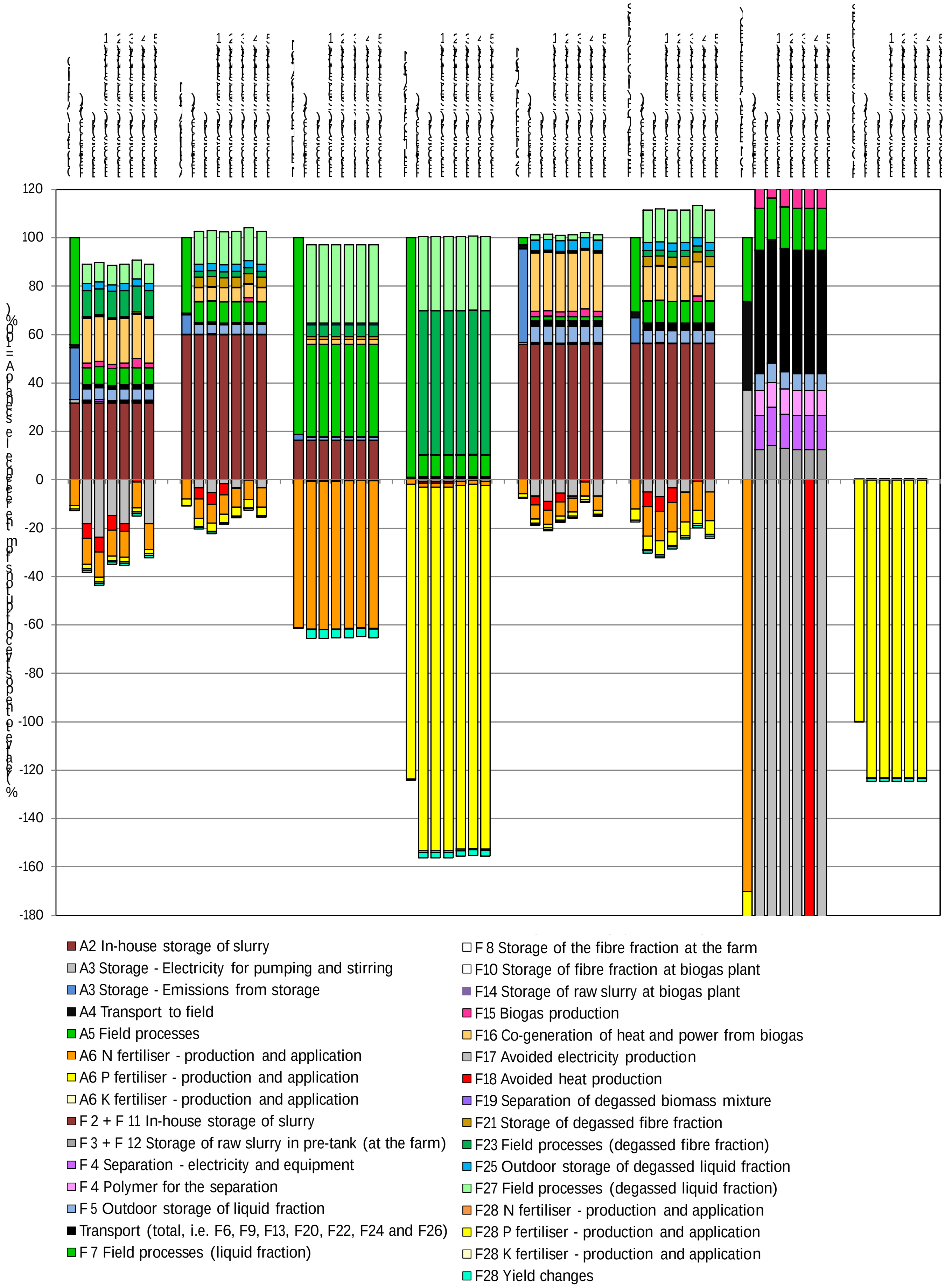
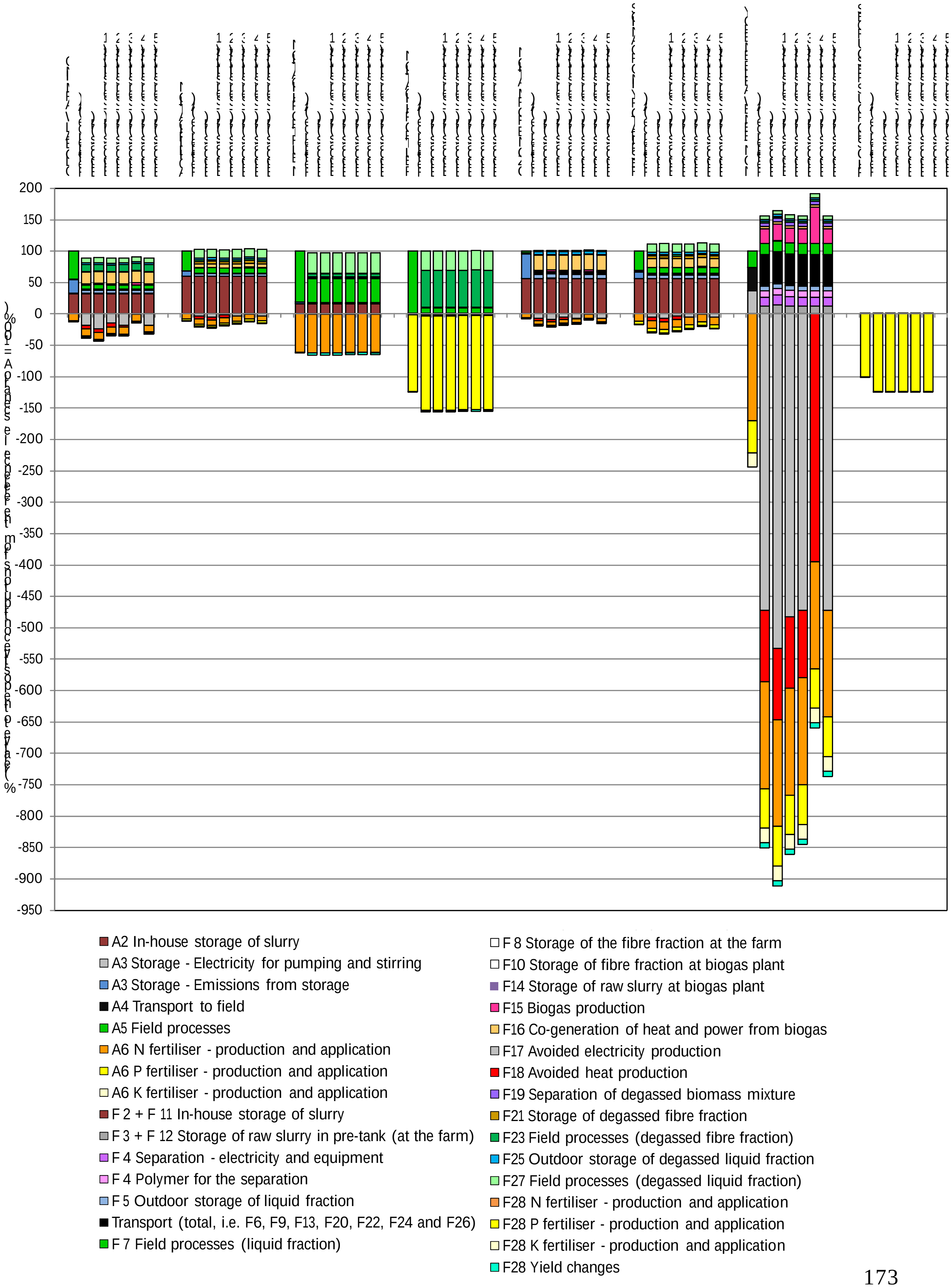


Figure 8.2.B
Sensitivity analysis: avoided heat and electricity, biogas utilisation and amount of usable heat.

Scenario F vs scenario A. Fattening pig slurry management. Soil type JB3. 10 years time horizon for global warming and for aquatic eutrophication (N). **Axis ranging from -950 to 200.**



8.2.4 Long term CO_2 emissions from anaerobic digestion residues

Regarding the long term (decades to a century) emission of CO_2 from various residues from biogas production, there is a lack of empirical data to support the model findings. It is a well-established fact that C from animal manure has a higher long-term retention than C from plant residues (e.g. Stemmer et al., 2000), which is supported by many independent long-term field trials. The same issue has, to our knowledge, not to date been investigated for biogas residues.

The present model simulations are based on the conservative assumption that the long-term retention equals that of C from animal manure. From a theoretical viewpoint, it may be argued that the retention is a bit higher for biogas residues, but this is not verifiable, neither can there be put a possible coefficient on this hypothetical effect.

If the retention should be higher than presumed here, it all in all would mean that the biogas system is slightly more favourable than estimated. But only results from possible, future long-term experiments can disclose that.

8.2.5 Avoided N fertiliser

Sensitivity analysis for alternative methods for calculating the replaced amount of mineral N fertiliser has been performed by a combination of rule a, c and d as mentioned in section F.28.2 of Annex F. The calculations are shown in tables 8.2-8.5 below:

- In table 8.2, rule c) has been applied (***"The producer of the degassed biomass (i.e. the biogas plant staff) sets the "mineral fertiliser replacement value" for the degassed biomass based on representative measurement of samples of the degassed biomass.")*.** It is assumed that the mineral fertiliser value of the degassed biomass corresponds to 90% of the N content in the degassed biomass. Rule a) still applies for the separation (the outgoing amount is identical to the ingoing amount).
- In table 8.3, rule d) has been applied, which is rather similar to the calculations in table 8.2 but with 75% instead of 90% for the fertiliser value of the degassed biomass.
- In table 8.4, rule d) has been applied, but it is assumed that all values are based on ***measured*** values of the N content instead of Norm Data values (as in table F.35 of Annex F). The measured values are assumed to be identical to the N content in the fractions.
- Table 8.5 gives an overview of the various sensitivity analysis and yield changes.

Table 8.2
Sensitivity analysis for the replaced amount of mineral N fertiliser in Annex F. All calculations per 1000 kg slurry ex-animal. Application of rule c).

Calculations
Step 1: Substitution value for fibre fraction to biogas plant Identical to Step 1 in table F.35. N in fibre fraction = 0.97017 kg N per 1000 kg slurry ex-animal.
Step 2: Acknowledging the above, make the weighted sum of the substitution values (liquid and fibre). For raw pig slurry, the substitution value is 75 %. Identical to Step 2 in table F.35. Mineral fertiliser replacement value for the liquid fraction (at the farm): **2.47135 kg N**
Step 3: Substitution values for the materials leaving the biogas plant. In this calculation, it is assumed that the producer of the degassed biomass (i.e. the biogas plant staff) sets the “mineral fertiliser replacement value” for the degassed biomass based on representative measurement of samples of the degassed biomass. The N content of the degassed biomass is 8.722 kg N per 1000 kg degassed biomass (table F.22). As can be seen in figure F.1, there is 319.84 kg degassed biomass. The substitution value for degassed biomass set to **90%** in these calculations, accordingly the mineral fertiliser replacement value for the degassed biomass is 8.722 kg N per 1000 kg degassed biomass * 319.84 kg degassed biomass * 90% = 2.5107 kg N. This value is used for the further calculations.
Step 4a: Use a substitution value of 50% for the fibre fraction of the degassed material from the biogas plant (like step 1) Amount of degassed fibre fraction: 77.272 kg (see figure F.1). N in degassed fibre fraction: 7.65 kg per 1000 kg fibre fraction (see table F.26). Substitution value: 50% * 7.65 kg per 1000 kg fibre fraction * 77.272 kg fibre fraction / 1000 kg = 0.2956 kg N per 1000 kg slurry ex-animal. Mineral fertiliser replacement value the degassed fibre fraction: **0.2956 kg N**
Step 4b: Calculation of the substitution value for the liquid fraction as “the rest”. Here, rule (a) applies again: “The sum of the “mineral fertiliser replacement value” of the outgoing fractions shall be the same as the “mineral fertiliser replacement value” of the ingoing slurry before separation”. • Total substitution value out of biogas plant = total substitution value in biogas plant, as calculated in step 3: 2.5107 kg N. • Substitution value for the liquid fraction = total from biogas plant – fibre fraction (from step 4a) = 2.5107 kg N - 0.2956 kg N = 2.2151 kg N Mineral fertiliser replacement value for the degassed liquid fraction (after the biogas plant: **2.2151 kg N**
Total amount of substituted mineral N fertiliser in the system 2.47135 kg N + 0.2956 kg N + 2.2151 kg N = **4.982 kg N**

Table 8.3
Sensitivity analysis for the replaced amount of mineral N fertiliser in Annex F. All calculations per 1000 kg slurry ex-animal. Application of rule d), norm data values.

Calculations
Step 1: Substitution value for fibre fraction to biogas plant Identical to Step 1 in table F.35. N in fibre fraction = 0.97017 kg N per 1000 kg slurry ex-animal.
Step 2: Acknowledging the above, make the weighted sum of the substitution values (liquid and fibre). For raw pig slurry, the substitution value is 75 %. Identical to Step 2 in table F.35. Mineral fertiliser replacement value for the liquid fraction (at the farm): **2.47135 kg N**
Step 3: Substitution values for the materials leaving the biogas plant. In this calculation, it is assumed that the producer of the degassed biomass (i.e. the biogas plant staff) sets the “mineral fertiliser replacement value” for the degassed biomass based on representative measurement of samples of the degassed biomass. The N content of the degassed biomass is 8.722 kg N per 1000 kg degassed biomass (table F.22). As can be seen in figure F.1, there is 319.84 kg degassed biomass. The substitution value for degassed biomass set to **75%** in these calculations, accordingly the mineral fertiliser replacement value for the degassed biomass is 8.722 kg N per 1000 kg degassed biomass * 319.84 kg degassed biomass * 75% = 2.0922 kg N. This value is used for the further calculations.
Step 4a: Use a substitution value of 50% for the fibre fraction of the degassed material from the biogas plant (like step 1) Amount of degassed fibre fraction: 77.272 kg (see figure F.1). N in degassed fibre fraction: 7.65 kg per 1000 kg fibre fraction (see table F.26). Substitution value: 50% * 7.65 kg per 1000 kg fibre fraction * 77.272 kg fibre fraction / 1000 kg = 0.2956 kg N per 1000 kg slurry ex-animal. Mineral fertiliser replacement value the degassed fibre fraction: **0.2956 kg N**
Step 4b: Calculation of the substitution value for the liquid fraction as “the rest”. Here, rule (a) applies again: “The sum of the “mineral fertiliser replacement value” of the outgoing fractions shall be the same as the “mineral fertiliser replacement value” of the ingoing slurry before separation”. • Total substitution value out of biogas plant = total substitution value in biogas plant, as calculated in step 3: 2.0922 kg N. • Substitution value for the liquid fraction = total from biogas plant – fibre fraction (from step 4a) = 2.0922 kg N - 0.2956 kg N = 1.7966 kg N Mineral fertiliser replacement value for the degassed liquid fraction (after the biogas plant: **1.7966 kg N**
Total amount of substituted mineral N fertiliser in the system 2.47135 kg N + 0.2956 kg N + 1.7966 kg N = **4.56355 kg N**

Table 8.4
Sensitivity analysis for the replaced amount of mineral N fertiliser in Annex F. All calculations per 1000 kg slurry ex-animal. Application of rule d), measured values.

Calculations
Step 1: Substitution value for fibre fraction to biogas plant Identical to Step 1 in table F.35. N in fibre fraction = 0.97017 kg N per 1000 kg slurry ex-animal.
Step 2: Acknowledging the above, make the weighted sum of the substitution values (liquid and fibre). For raw pig slurry, the substitution value is 75 %. The calculations are identical to the calculations in table F.35 except for that instead of using the Danish Norm Data for the N content of the raw pig slurry, the measured values has been used, i.e. 4.80 kg N per 1000 kg slurry ex storage (table A. 1) instead of 5.00 kg N per 1000 kg slurry ex storage (table A. 1). The calculations follow the calculations in table F.35: For the system, the mineral fertiliser substitution value is then: 4.80 kg N per 1000 kg slurry ex storage * 1086 kg slurry ex storage / 1000 kg slurry ex animal * 75% = 3.9096 kg N per 1000 kg slurry ex-animal. However, there is only 845.064 kg slurry being separated (see figure F.1), i.e. 3.9096 kg/1000 kg * 845.064 kg = 3.30386 kg N. • Of this 3.30386 kg N, 0.97017 kg N belongs to the fibre fraction (as calculated in step 1). • The difference i.e.: 3.30386 kg N – 0.97017 kg N = 2.33369 kg N belongs to the liquid fraction. Mineral fertiliser replacement value for the liquid fraction (at the farm): **2.33369 kg N**
Step 3: Make a weighed sum of the substitution values for the materials entering the biogas plant. Rule (b): “Mass balance in and out of Biogas Plant – i.e. the “mineral fertiliser replacement value” of the outgoing biomass is calculated in accordance with the ingoing biomass”. • The raw slurry going directly to biogas plant (without separation) has a mineral fertiliser replacement value of 3.9096 kg N per 1000 kg slurry (as described under step 2 above – 75% of 4.80 kg N ex storage). The amount of this raw slurry is 154.936 kg (see figure F.1). Its mineral fertiliser replacement value is: 3.9096 kg N per 1000 kg slurry * 154.936 kg slurry/1000 kg = 0.60574 kg N per 1000 kg slurry ex-animal. This is the substitution value for the raw slurry into the biogas plant. • At the plant, a biomass mixture is made from this raw slurry and the fibre fraction from step 1, so the substitution value for this input mixture is: 0.97017 kg N (fibre fraction, step 1) + 0.60574 kg N (raw slurry, see above) = 1.57591 kg N. This is the substitution value for the input biomass mixture going into the biogas plant, and accordingly also the substitution value for the degassed biomass mixture coming out of the biogas plant – i.e. the degassed biomass before separation. This value is used for the further calculations.
Step 4a: Use a substitution value of 50% for the fibre fraction of the degassed material from the biogas plant (like step 1) Amount of degassed fibre fraction: 77.272 kg (see figure F.1). N in degassed fibre fraction: 7.65 kg per 1000 kg fibre fraction (see table F.26). Substitution value: 50% * 7.65 kg per 1000 kg fibre fraction * 77.272 kg fibre fraction / 1000 kg = 0.2956 kg N per 1000 kg slurry ex-animal. Mineral fertiliser replacement value the degassed fibre fraction: **0.2956 kg N**
Step 4b: Calculation of the substitution value for the liquid fraction as “the rest”. Here, rule (a) applies again: “The sum of the “mineral fertiliser replacement value” of the outgoing fractions shall be the same as the “mineral fertiliser replacement value” of the ingoing slurry before separation”. • Total substitution value out of biogas plant = total substitution value in biogas plant, as calculated in step 3: 1.57591 kg N. • Substitution value for the liquid fraction = total from biogas plant – fibre fraction (from step 4a) = 1.57591 kg N - 0.2956 kg N = 1.28031 kg N Mineral fertiliser replacement value for the degassed liquid fraction (after the biogas plant: **1.28031 kg N**
Total amount of substituted mineral N fertiliser in the system 2.33369 kg N + 0.2956 kg N + 1.28031 kg N = **3.9096 kg N**

Table 8.5
Sensitivity analyses for the replaced amount of mineral N fertiliser in Annex F. All calculations per 1000 kg slurry ex-animal. Overview of all results.

Description of the sensitivity analysis	Amount of replaced mineral N fertiliser kg N per 1000 kg slurry ex animal
Base case (table F.35, Annex F)	4.0725 kg N
Sensitivity 1 (Table 8.2): Rule c) has been applied *("The producer of the degassed biomass (i.e. the biogas plant staff) sets the "mineral fertiliser replacement value" for the degassed biomass based on representative measurement of samples of the degassed biomass.").* It is assumed that the mineral fertiliser value of the degassed biomass corresponds to 90% of the N content in the degassed biomass.	4.982 kg N
Sensitivity 2 (Table 8.3): Rule d) has been applied, which is rather similar to the calculations in table F.37 but with 75% instead of 90% for the fertiliser value of the degassed biomass.	4.564 kg N
Sensitivity 3 (Table 8.4): Rule d) has been applied, but it is assumed that all values are based on measured values of the N content	3.9096 kg N

The different methods for how the amount of avoided N fertiliser is calculated do not change the overall conclusions, which is illustrated in figures 8.3.A and 8.3.B, where the results for Scenario A, Scenario F, sensitivity 1 and sensitivity 3 are compared. It can be seen that if the amount of avoided N fertiliser is increased it will just reduce the yield, which will to some extend counteract for the increased amount of avoided N.

Or, to explain this further: When applying pig slurry, the N in the slurry replace 75% mineral fertiliser, which means that if applying 100 kg N in slurry, the farmer has to apply 75 kg mineral N fertiliser less (Gødskningsbekendtgørelsen (2008), paragraph 21). For example, if the farmer has a field with winter barley, and the soil type is JB3, the farmer has a "Nitrogen quota" for that field at 149 kg N per ha (Plantedirektoratet, 2008). If the farmer applies 100 kg N per ha as pig slurry, this accounts for 75 kg N per ha, which means that the farmer is allowed to apply the remaining 149 kg N per ha – 75 kg N per ha = 74 kg N per ha as mineral N fertiliser. In consequence, the farmer is interested in that the "mineral fertiliser replacement values" of the slurry are as ***small*** as possible as this will increase the yield.

When the yield is increased, the extra yield is subtracted from the system. The increase of a crop yield of is assumed to replace winter wheat produced somewhere else in Denmark. This is a very simplified assumption. The consequences of increased crop yield probably replace another crop type somewhere else in the world. It is beyond the frame of this project to identify the avoided crop as a consequence of the increased crop yield. In this report, it is assumed that the increased crop yield replace winter wheat, using data from the process "Wheat, conventional, from farm" from LCA-food data base (modified with the updated data for production of fertilisers as described in Annex A in Wesnaes et. al (2009)).

Figure 8.3.A
Sensitivity analysis: Replaced amount of mineral N.
Scenario F vs scenario A. Fattening pig slurry management. Soil type JB3. 10 years time horizon for global warming and for aquatic eutrophication (N). **Axis ranging from -180 to 120.**

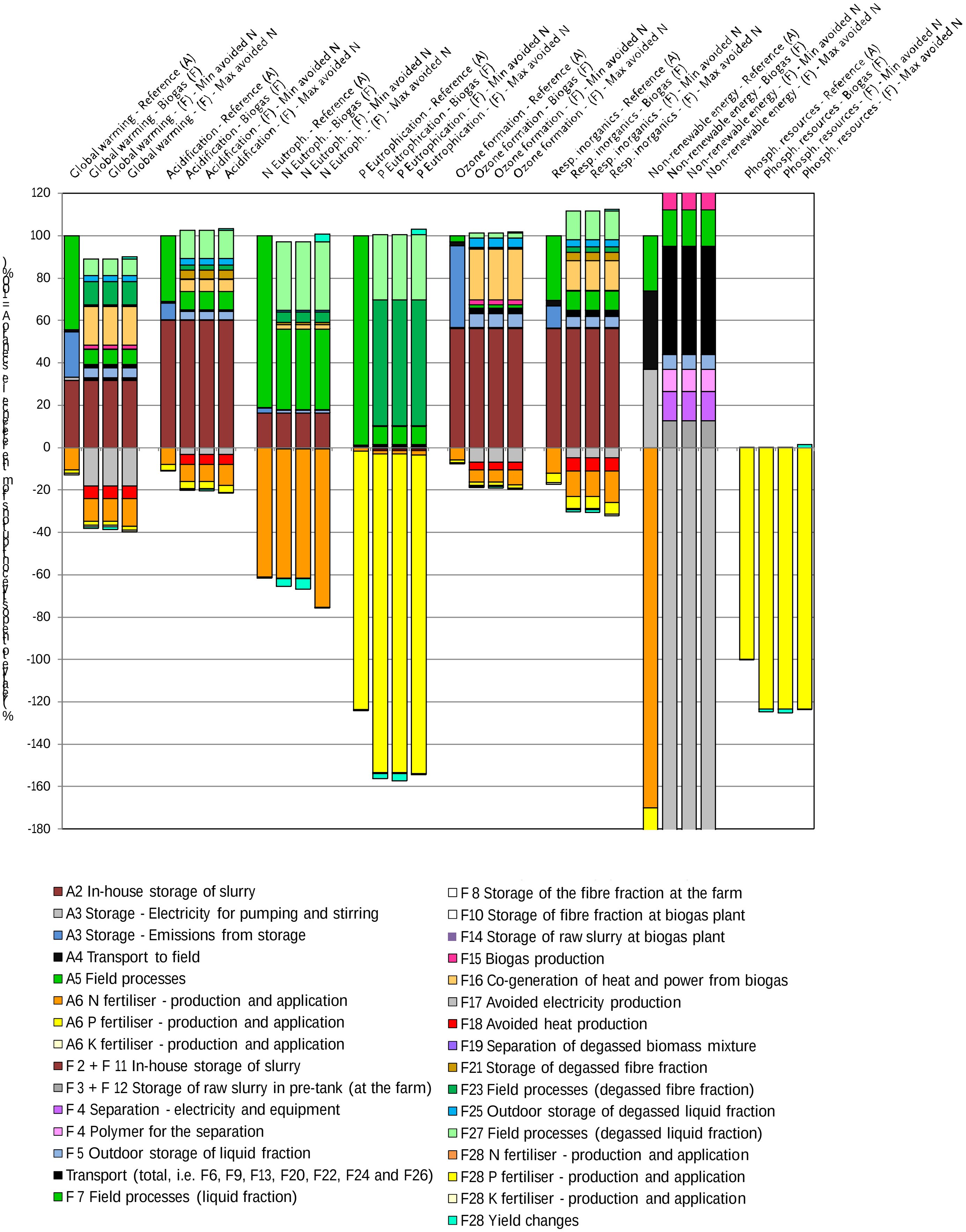
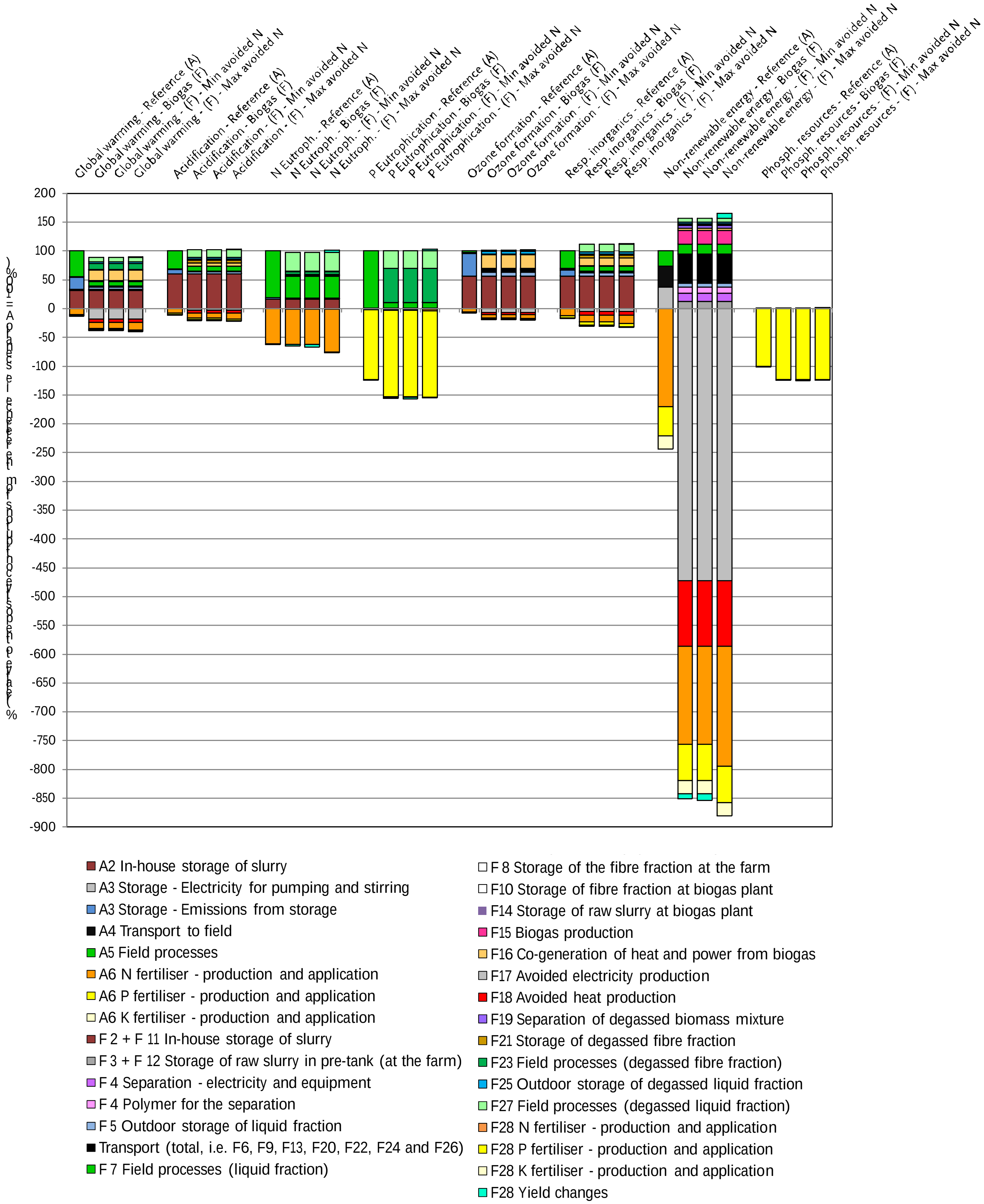


Figure 8.3.B
Sensitivity analysis: Replaced amount of mineral N.
Scenario F vs scenario A. Fattening pig slurry management. Soil type JB3. 10 years time horizon for global warming and for aquatic eutrophication (N). **Axis ranging from -900 to 200.**



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Annex F. Biogas production with pig slurry and fibre fraction from a mechanical-chemical separation– Life Cycle Inventory data

F.1 System description

This annex contains Life Cycle Inventory data for biogas production from a mixture of fibre fraction (from mechanically separated slurry, flocculated with polymer) and raw slurry, both from fattening pigs. The separation process used in this annex is considered as a “best available technology” for biogas production. The resulting fibre fraction has a degradation potential similar to the one of raw slurry. The biogas is used for co-production of heat and power. The biogas engine used for the generation of heat and power is also considered as a “best available technology”, as the engine used has conversion efficiencies ranking in the highest available range. The processes described and used for this scenario were built in collaboration with Xergi A/S, as Xergi A/S has experience and data for more than 30 biogas plants established throughout the country. The degassed slurry resulting from the anaerobic digestion is mechanically separated again, but without polymer addition. The liquid fraction is then used on field as a fertilizer, and so is the fibre fraction.

Although biogas exclusively from slurry input (i.e. without supplementary addition of easily degradable carbon) is not yet the most common practice in Denmark, it is likely to become an important alternative for the Danish panorama. This is due to the limited availability of the organic waste or the other C-source materials that are actually co-digested with the slurry. Co-digesting the raw slurry is practiced in order to ensure the economic feasibility of biogas production. Moreover, the Danish government has set the objective to use more than 50 % of the slurry produced in Denmark for biogas production, in which case the possibility to make biogas from 100 % slurry input represents an interesting option. Several plants running on inputs from slurry only (i.e. raw slurry and separated fibre fraction) are currently under development throughout the country, and the first one has just been put into operation (Morsø Bioenergi was inaugurated 15 of June 2009).

The present annex describes the process flow for a biogas scenario comprising a total of 28 main processes, which were divided into 8 main sections:

- Section 1 : Processes F.2 to F.7
  This section focus on the slurry from which the fibre fraction input in the biomass mixture (for biogas) origins. It starts with the raw slurry being produced in the pig barn and stored in the barn (F.2). The slurry is then stored in the pre-tank (F.3) and separated (F.4). This section then continues with the fate of the liquid fraction only. The liquid fraction is stored outdoor (F.5), until it is transported to the field (F.6) and used as a fertilizer (F.7).
- Section 2 : Processes F.8 to F.10
  This section is a continuation of the previous, and starts with the fibre fraction output from the separation process (F.4). The fibre fraction is stored on-farm (F.8), transported to the biogas plant (F.9) and temporarily stored at the biogas plant (F.10).
- Section 3 : Processes F.11 to F.14
  This section focus on the raw slurry input in the biomass mixture (for biogas). It begins with the raw slurry being produced in the pig barn and stored in the barn (F.11). The slurry is then stored in pre-tank at the farm (F.12), and transported to the biogas plant (F.13). Once at the biogas plant, the raw slurry is stored temporarily (F.14).

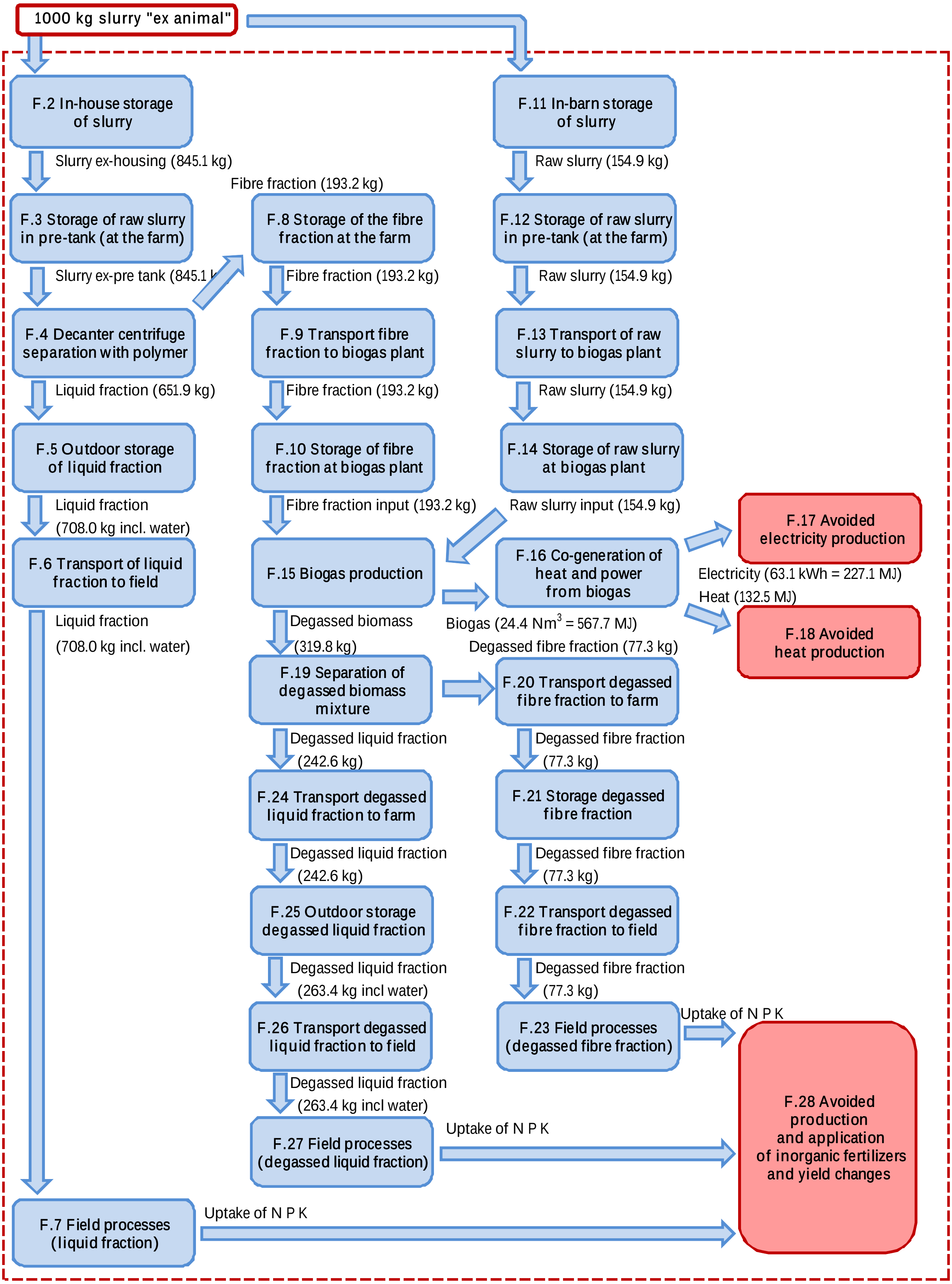
- **Section 4 : Processes F.15 to F.18**
  This section focuses on the biogas production (F.15) and the resulting heat and power co-generation (F.16). This co-generation avoids marginal electricity to be produced (F.17) as well as marginal heat (F.18).
- **Section 5 : Process F.19**
  This section describes the separation of the degassed biomass mixture output from the anaerobic digestion (F.19).
- **Section 6 : Processes F.20 to F.23**
  This section focuses on the fate of the degassed fibre fraction. After the separation, it is transported to a farm where a fertilizer rich in P is needed (F.20), stored (F.21) until it is transported to the field (F.22) to be used as a fertilizer (F.23).
- **Section 7 : Processes F.24 to F.27**
  This section focuses on the fate of the degassed liquid fraction. After the separation, it is transported back to the farm (F.24), stored (F.25) until it is transported to the field (F.26) to be used as a fertilizer (F.27).
- **Section 8: Process F.28**
  Throughout this annex, three organic fertilizers were used: a liquid fraction (F.7), a degassed liquid fraction (F.27) and a degassed solid fraction (F.23). The use of these organic fertilizers allowed to avoid inorganic fertilizer to be produced and used (F.28), which is the main focus of this section.

The scenario described in this annex has been modelled in order to include “Best Available Technology” as much as possible. The conditions considered throughout the scenario were chosen in the light of the best feasible possibilities. This applies for the technologies used as well as for the management practices. However, conservative assumptions were used in the calculation of the emissions, in order to ensure the life cycle assessment reflects the correct picture as regarding the environmental consequences of this manure management option.

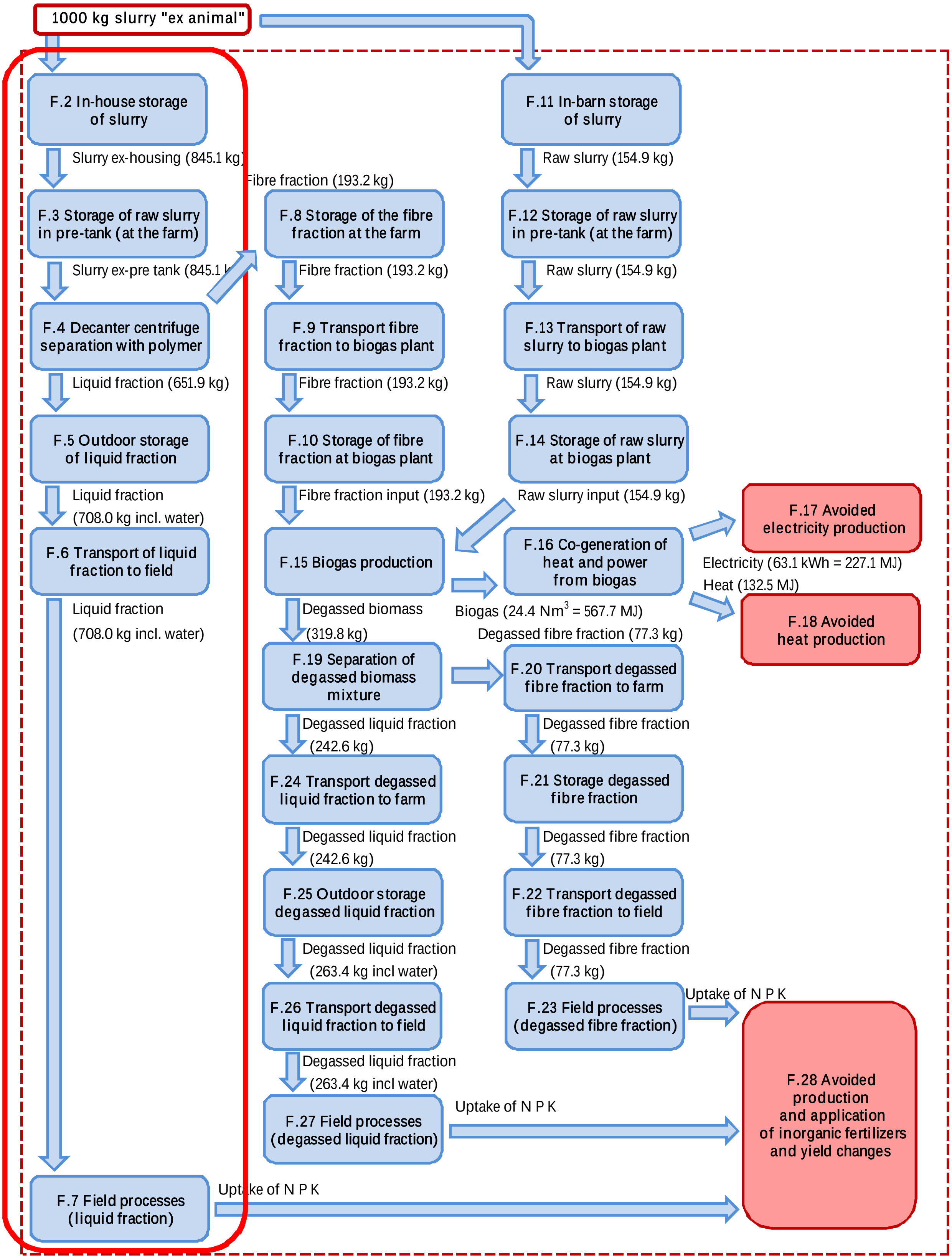
It shall also be mentioned that many possibilities could have been included as regarding the different variants in the biogas production, which could be worth another life cycle assessment themselves. For example, instead of being used for co-generation of heat and power through a biogas engine, the biogas could have been cleaned and injected directly to the natural gas grid (this possibility is however considered as a sensitivity analysis). Else, it could also have been upgraded and used as a transportation fuel. Also, the slurry is sometimes treated in a pre-treatment plant before entering the biogas plant, which is another variant not included here.

The overall flow diagram for this scenario is presented in figure F.1.

Figure F.1.
Flow diagram for biogas production based on raw slurry + fibre fraction from mechanically separated pig slurry with a decanter centrifuge and polymer addition



Processes F.2 to F.7: Raw slurry from which the fibre fraction origins: production, separation and fate of the liquid fraction



F.2 In-house storage of slurry

The assumptions and Life Cycle Inventory data for the storage of slurry in the housing units are the same as for the reference scenario (section A.2, Annex A). Accordingly, the CH_4 and N_2O emissions are calculated with the IPCC guidelines (IPCC, 2006).

For CH_4, the calculation is thus as follows: CH_4 [kg] = VS [kg] * B_0[1] * 0.67 [kg CH_4 per m^3 CH_4] * MCF [2], with the "ex animal" VS and with MCF = 17 % (value for pit storage below animal confinement greater than 1 month, table 10.17 in IPCC 2006). The choice of a MCF value of 17 %, as explained in Annex A (section A.2), is conservative, the alternative being a MCF = 3 % if the storage is less than one month, based on IPCC (2006) tabulated values. The gap between these two alternative MCF values is considerable. This means that the overall greenhouse gas emissions related to the in-house storage presented in this study, if compared to other studies, may be significantly higher based on the choice of this MCF value. Yet, systems need to be comparable, so the alternatives assessed hereby must be assessed as in the reference scenario.

As the in-house storage of slurry is identical to the one in the reference case, performing a sensitivity analysis with a lower MCF would only contribute to reduce the CH_4 emissions of both the present and the reference scenario by the same order of magnitude. Instead, the effect of this conservative choice for the MCF value is raised as a discussion point in the interpretation of the results. It is however acknowledged that the CH_4 emissions during in-house storage could have been estimated with an Arrehenius relationship, as proposed by Sommer et al. (2004) and Sommer et al. (2009) instead of the IPCC methodology.

For direct N_2O emissions, IPCC (2006) estimates the N_2O emissions from pit storage below animal confinements to be 0.002 kg N_2O-N per kg N "ex animal" (uncertainty: a factor 2), based on the judgement of an IPCC expert group combined with various studies. The indirect N_2O emission corresponds to 0.01 kg N_2O–N per kg (NH_3–N + NO_X–N volatilised) (IPCC, 2006, table 11.3).

The NO-N and N_2-N emissions were calculated in the same way as in Annex A, i.e. based on the study of Dämmgen and Hutchings (2008). In their study,

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[1] B_0 : maximum methane producing capacity for manure produced, corresponds to 0.45 m^3 CH_4/kg VS ex-animal for market swine (IPCC 2006, table 10A-7).

[2] MCF: methane conversion factor (%). The MCF factor is defined in the IPCC (IPCC, 1997) guidelines in chapter 4 (on page 4.9) as follows :
"Methane Conversion Factor (MCF): The MCF defines the portion of the methane producing potential (Bo) that is achieved. The MCF varies with the manner in which the manure is managed and the climate, and can theoretically range from 0 to 100 per cent. Manure managed as a liquid under hot conditions promotes methane formation and emissions. These manure management conditions have high MCFs, of 65 to 90 per cent. Manure managed as dry material in cold climates does not readily produce methane, and consequently has an MCF of about 1 per cent. Laboratory measurements were used to estimate MCFs for the major manure management techniques."

they assumed that the emission of nitrogen monoxide (NO) is the same as the direct emission of nitrous oxide (N_2O) (measured as NO-N and N_2O-N). Furthermore, they assumed that emission of nitrogen (N_2) is three times as high as the direct emissions of nitrous oxide (N_2O) (measured as N_2-N and N_2O-N).

As regarding the total NO_x emissions ($NO_x = NO + NO_2$), it was assumed, as in Annex A, that $NO_x = NO$. This is because it has not been possible to find data on NO_2.

Ammonia emissions are estimated based on Poulsen et al. (2001), where an emission factor of 16% NH_3-N of the total N ex-animal is suggested for fattening pigs on fully slatted floors.

Emissions of CO_2 are based on mass balances, i.e. as the total loss of carbon in the housing units minus the carbon lost as CH_4 emissions. The total loss of carbon in the housing units is 3.4 kg (table A.7, Annex A), so this gives a CO_2 emission of 3.44 kg/1000 kg slurry ex-housing (see calculation in table F.1).This mass balance approach is used because the slurry composition for C was determined backwards, i.e. from the C content of ex-storage slurry through the C content of ex-housing slurry and finally ex-animal slurry. This backwards approach was used due to the availability of data. Estimating the CO_2 emissions for the in-house storage with another approach than the mass balance would therefore change the ex-housing manure composition, which is the very basis of comparison between all scenarios. Yet, in subsequent anaerobic storages of slurry, the CO_2 emissions are estimated as a function of the CH_4 emissions (i.e. sections F.5, F.15 and F.25). If the in-house CO_2 production would had been calculated in accordance with the CO_2:CH_4 ratio as described in section F.5 (i.e. 1.42 g of CO_2 is produced per g of CH_4) the CO_2 emission here would have been 4.67 kg CO_2(1.42 kg CO_2/kg CH_4 x 3.29 kg CH_4). Compared to the actual 3.44 kg CO_2, the difference is not significant for the overall results. Accordingly, the current method for calculation of the CO_2 emission from slurry stored in the barn does not influence the overall results.

Moreover, part of the produced CO_2 from the in-house storage (and also outdoor storage) is emitted to air immediately and part of the CO_2 is dissolved in the slurry. In this life cycle assessment, it is calculated as all the CO_2 is emitted to air immediately. By calculating this way, the CO_2 will be emitted at the process that causes the CO_2, which makes the interpretation of the sources easier. Furthermore it does not change the overall result, as the overall amount of CO_2 emitted is exactly the same. The only difference is that it would have been emitted at a later stage in the life cycle chain of the slurry. The same approach has been used in Annex B, see section B.2.

Table F.1 (taken from Annex A), shows the life cycle data for the in-house storage of raw slurry.

Table F.1.
Life cycle Inventory data for storage of raw slurry in the housing units. All data per 1000 kg of slurry “ex animal”. (taken from Annex A, table A.9)

	Fattening pig slurry	Comments
Input		
Slurry “ex animal”	1000 kg	The input to this process is 1000 kg slurry “ex animal”. This is the reference amount of slurry. The emissions are calculated relative to this.
Output		
Slurry “ex housing”	1000 kg	Here, the output mass is the same as the input mass. Deviations due to added water and emissions are not included in the total mass, see the discussion before table A.4., section A.1.2 in Annex A.
Energy consumption		
	Not included	The energy consumption for the housing units is not included within the system boundary.
Emissions to air		
Carbon dioxide (CO_2)	3.44 kg	Estimated as total loss of C minus CH_4 emissions (given below): 3.4 kg C – (3.29 kg CH_4*[12.011/16.033]) = 0.94 kg CO_2-C * (44.009/12.011) = 3.44 kg.
Methane (CH_4)	3.29 kg	IPCC (2006) Tier 2 approach with MCF = 17 %, see text. CH_4 = 64.2 kg VS/1000 kg slurry * 0.45 m^3 CH_4/kg VS * 0.67 kg CH_4/m^3 CH_4 * 17 % = 3.29 kg. (VS ex-animal is from table A.1, Annex A).
Ammonia (NH_3-N)	1.06 kg	Based on Poulsen et al. (2001). For fattening pig slurry (fully slatted floor):16% NH3-N of the total-N “ex animal”: 6.6 kg N/1000 kg slurry ex-animal * 16 % = 1.06 kg.
Direct emissions of Nitrous oxide (N_2O-N)	0.013 kg	0.002 N_2O-N per kg N “ex animal” (IPCC, 2006): 6.6 kg N/1000 kg slurry ex-animal * 0.002 = 0.0132 kg.
Indirect emissions of Nitrous oxide (N_2O-N)	0.011 kg	0.01 kg N_2O–N per kg of (NH_3–N + NO_X–N) volatilised (IPCC, 2006, table 11.3). Ammonia and NO emissions given in this table.
Nitrogen monoxide (NO-N) (representing total NO_X)	0.013 kg	Estimate based on Dämmgen and Hutchings (2008), consisting of assuming that NO-N = (direct) N_2O-N * 1, see text.
Nitrogen dioxide (NO_2-N)	No data	No data.
Nitrogen (N_2-N)	0.039 kg	Estimate based on Dämmgen and Hutchings (2008), consisting of assuming that N_2-N = (direct) N_2O-N * 3, see text.
Discharges to water		
	None	Assumed to be zero, as leakages from housing systems are prohibited in Denmark.
Discharges to soil		
	None	Assumed to be zero, as leakages from housing systems are prohibited in Denmark.

F.3 Storage of slurry in pre-tank

The raw slurry ex-housing is stored in the pre-tank, and will later be directly pumped from there when transferred to the separation unit. No significant losses from the pre-tank storage as well as no water addition are assumed; it is thus consistent with section C.3 in Annex C (storage of slurry in pre-tank before separation with the Samson Bimatech technology).

The exact duration of the storage in the pre-tank is, in practice, quite variable, from a few days to a few weeks, according to the contracts farmers have with the biogas plants regarding the deliveries. According to Rosager (2009), assuming a storage duration of maximum 10 to 14 days in the pre-tank would be a reasonable, though conservative, assumption. This assumption was therefore applied in this project.

Assuming no losses may be reasonable for this duration period, but it may not be correct for a longer storage period, particularly as regarding losses of C (through CH_4 and CO_2).

In fact, Møller et al. (2004), who estimated the losses of carbon from in-house storage of both pig and cattle manure in a laboratory-scale study, reported the losses of both CO_2 and CH_4 as a function of the storage time. From the graphs presented in Møller et al. (2004), it can be seen that an emission peak (for both CH_4 and CO_2) occurs between 10 and 20 days after excretion (storage at 15°C). In the case of this project, no specific storage duration was assumed for the in-house storage (it was only assumed that it is less than 1 month, see section A.2.2 of Annex A), but it appears likely that the emission peak presented in Møller et al. (2004) for CH_4 did occur during the in-house storage (i.e. before the slurry was transferred to the pre-tank). Moreover, important CH_4 emissions were considered during the in-house storage of the slurry (as a methane conversion factor of 17% was used in the calculation, see discussion in section F.2). Given these facts, it appears reasonable to assume no additional methane losses for the pre-tank storage phase.

The energy consumption related to the slurry transfer from the pre-tank through the separation unit involves the electricity for stirring in the pre-tank before pumping (1.2 kWh per 1000 kg slurry ex-housing, as in table A.10 of Annex A) and the electricity for pumping (0.5 kWh per 1000 kg slurry ex-housing, as in table A.10 of Annex A). This involves a total energy consumption of 1.7 kWh per 1000 kg slurry ex-housing.

The life cycle data for the storage of the slurry in the pre-tank are presented in table F.2. The ex pre-tank slurry composition considered is presented in table F.3 (which is identical to the ex-housing slurry of Annex A, table A.1).

Table F.2.
Life cycle Inventory data for storage of raw slurry in the pre-tank. All data per 1000 kg of slurry "ex animal".

	Fattening pig slurry	Comments
Input		
Slurry "ex housing"	1000 kg	The input to this process is 1000 kg slurry "ex animal". This is the reference amount of slurry. The emissions are calculated relative to this.
Output		
Slurry "ex pre-tank"	1000 kg	Here, the output mass is the same as the output mass. Deviations due to added water and emissions are not included in the total mass, see the discussion before table A.4., section A.1.2 in Annex A.
Energy consumption		
Electricity	1.7 kWh	Electricity for stirring and pumping
Emissions to air		
Carbon dioxide (CO_2)	Negligible	Considered as negligible, see text.
Methane (CH_4)	Negligible	Considered as negligible, see text.
Ammonia (NH_3-N)	Negligible	Considered as negligible, see text.
Direct emissions of Nitrous oxide (N_2O-N)	Negligible	Considered as negligible, see text.
Indirect emissions of Nitrous oxide (N_2O-N)	Negligible	Considered as negligible, see text.
Nitrogen monoxide (NO-N) (representing total NO_X)	Negligible	Considered as negligible, see text.
Nitrogen dioxide (NO_2-N)	Negligible	Considered as negligible, see text.
Nitrogen (N_2-N)	Negligible	Considered as negligible, see text.
Discharges to water		
	None	Assumed to be zero, as leakages from housing systems are prohibited in Denmark.
Discharges to soil		
	None	Assumed to be zero, as leakages from housing systems are prohibited in Denmark.

Table F.3.
Characteristics of slurry ex pre-tank from fattening pigs
Per 1000 kg of slurry ex pre-tank

	Slurry ex pre-tank
Total mass	1000 kg
Dry matter (DM)	69.7 kg
Ash content	13.2 kg
Volatile solids (VS) Of total VS: - easily degradable - heavy degradable	56.5 kg 34.0 kg 22.5 kg
Total-N (DJF, 2008)	*No data (calculated: 5.54 kg)*
Total-N in this study	5.48 kg
$NH4^+$-N	No data
Total-P	1.13 kg
Potassium (K)	2.85 kg
Carbon (C)	33.3 kg
Copper (Cu)	30.0 g
Zinc (Zn)	89.4 g
Density	1053 kg per m^3
pH	7.8

F.4 Separation by a decanter-centrifuge separator combined with the use of polymer

F.4.1 Description of the separation technology

The GEA Westfalia separation process, which is used in this study, is based on centrifugal separation technology. The present scenario is calculated based on data from a UCD 305 decanter centrifuge. It contains a horizontally oriented, conical rotor constructed in a manner allowing for continuous removal of separated material. The centrifugal force makes particulate matter move towards the perimeter of the centrifuge, while the liquid fraction moves vertically through the centrifuge. Adding polymer, especially polyacrylamide (PAM) to the slurry input prior to the separation process contribute to increase the relative fraction of dry matter and nutrients transferred to the fibre fraction (Martinez-Almela and Barrera, 2005; Campos et al., 2008; Vanotti et al., 2002; Vanotti et al., 2005; González-Fernández et al., 2008). The present scenario is based on a relatively high polymer consumption (0.90 kg polymer addition per 1000 kg slurry input in the separation process, see table F.8).

F.4.2 Separation indexes and mass balances

It is assumed that the composition of the slurry leaving the pre-tank is the same as the “ex housing” composition in the reference scenario, as it has been assumed that there are no loss or emissions during the storage in the pre-tank (section F.3). This assumption is not strictly correct due to the biological processes in the slurry during the residence time in the pre-tank, as discussed in section C.3 of Annex C.

The efficiencies of the separation must be known in order to evaluate the composition of the subsequent liquid and solid fraction. In order to do so, data provided by GEA (GEA, 2009) were used, which are presented in table F.4. Values in table F.4 are based on measurements performed from raw slurry and solid fraction samples, and may therefore involve some inconsistencies when performing the whole mass balances, due to unavoidable experimental errors occurring during the sampling and related to measurement equipments. This is a general problem when performing measurements on separation data, and as described in Annex C, this also applies for literature data.

Table F.4.
Experimental data provided by GEA (chemical-mechanical separation of pig slurry).

	Fibre fraction	Liquid fraction
Total mass distribution	14.3-20.0%	80-83.6%
Dry matter (DM) distribution	87.2%	12.8%
Total-N distribution	41.9%	58.1%
Ammonium-N distribution	16.7%	83.3%
Phosphorous (P) distribution	90% [a)]	10%
Potassium (K) distribution	14.2%	85.8%
DM in the fibre fraction	26.59%	--

a) The separation index for phosphorus is based on the phosphorus mass balances for the liquid fraction (data provided by GEA) and not on the separation indexes data provided by GEA, as the separation index was 100% in spite of that there were still phosphorus in the liquid fraction after the separation.

The efficiency of separation is typically measured as the “separation index”. The separation index is the mass of a compound in the solid fraction divided by the mass of the compound in the original slurry before separation, e.g.

$$\text{Separation index for N (\%)} = \frac{\text{kg N in solid fraction}}{\text{kg N in slurry before separation}} * 100\%$$

The separation index for a given element can be interpreted as the percentage of the total amount of that parameter in the raw slurry that ends up in the solid fraction. The remaining is ending up in the liquid fraction (i.e. percentage in liquid fraction = 100 % - separation index).

In this project, the separation efficiencies will be based the data shown in table F.4, except for the total mass. The reason for this is that the amount of water in the slurry given by the “Danish Norm Data” for pig slurry (which is used as reference in this study) is far lower than the amount of water in the slurry that was used for the measurements by GEA. As described in Annex A, the reference pig slurry in the present study is based on the Danish Norm Data (Poulsen et al. (2001), DJF (2008a) and DJF (2008b)), and water from the housing units – used for cleaning - is not included in the Norm Data (the amount of water that is not included is probably in the order of 220 litres of water per 1000 kg pig slurry [3]). Yet, water contributes significantly to the total mass, so an adjustment is needed for the mass separation index.

In order to do so, it was assumed that the DM of the solid fraction coming out of the separator would remain approximately constant independently of the water content of the raw slurry. Based on this, the total mass of fibre fraction can be evaluated, and thereby the separation index for the total mass. Since the amount of DM in the fibre fraction was measured (26.59 %, which means that there is 265.9 kg DM per 1000 kg of fibre fraction), and since the DM content of the input slurry is known (69.7 kg DM per kg raw slurry, table A.1, Annex A), the mass of fibre fraction produced can be calculated. This amounts to 228.58 kg fibre fraction per 1000 kg raw slurry[4], which means that 22.858 % of the initial mass is found in the solid fraction. The remaining mass is then going in the liquid fraction, corresponding to 77.142 % (i.e. 100 % - 22.858 %).

Of course, this separation index for the mass will result in a lower water content of the liquid fraction as compared to the measurements performed by GEA(due to the relatively low water content of the reference slurry). As the emissions and field processes are calculated in relation to the amount of N

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[3] The exact amount is not known. From table A.4 in Annex A, an estimate based on data from Poulsen et al. (2001) indicates that water added in the housing units corresponds to approximately 223 litres per 1000 slurry. Poulsen et al. (2001) do not include this amount.

[4] The input slurry contains 69.7 kg DM/1000 kg raw slurry (Annex A). Yet, 87.2% of the DM ends up in the fibre fraction (see table F.4) i.e. 69.7 kg * 87.2% = 60.7784 kg DM per 1000 kg raw slurry. As the fibre fraction contains 265.9 kg DM per 1000 kg fibre fraction (due to measurements), the total amount of fibre fraction is: 60.7784 kg DM / 1000 kg raw slurry * 1000 kg fibre fraction/ 265.9 kg DM = 228.58 kg fibre fraction per 1000 kg raw slurry.

and C, the water content (not the concentration) is relatively unimportant for the overall results.

From the experimental data presented in table F.4, it can be noticed that the efficiencies for C, Cu and Zn cannot be evaluated as there are no data. Therefore, it was assumed that the separation efficiency for C is the same as for DM, i.e. 87.2 %. For Cu and Zn, separation efficiencies given in a recent study of Møller et al. (2007b) were used (centrifuge, pig slurry no.1). Since no polymer addition is involved in the study performed by Møller et al. (2007b), these efficiencies may be lower as those involved in the actual study, but it is yet a better approximation than simply ignoring Cu and Zn for the rest of the analysis.

Table F.5 presents the separation efficiencies considered in this study.

Table F.5.
Separation efficiencies considered for the chemical-mechanical separation of pig slurry.

	Percentage in the fibre fraction	Remark
Total mass	22.858 %	Calculated, see text.
Dry matter (DM)	87.2%	From experimental data (Table F.4)
Total-N	41.9%	From experimental data (Table F.4)
Ammonium-N	16.7%	From experimental data (Table F.4)
Phosphorous (P)	90%	From experimental data (Table F.4)
Potassium (K)	14.2%	From experimental data (Table F.4)
Carbon (C)	87.2%	Assumed to be the same as for DM
Cooper (Cu)	36.2 %	From Møller et al. (2007b)
Zinc (Zn)	42.2 %	From Møller et al. (2007b)

The mass balance calculations and composition of the resulting liquid and solid fractions are presented in table F.6.

Table F.6
Mass balances for gea separation of slurry from **fattening pigs** (Decanter centrifuge + polymer)
Per 1000 kg of slurry “ex housing”.

	Amount in slurry Ex pre-tank BEFORE separation i.e. “ex housing values from table A.1 in Annex A	Separation index (i.e. percentage transferred to fibre fraction) (from table F.5)	Mass Balance: Amount transferred to the fibre fraction	Mass balance: Amount transferred to the liquid fraction	Composition of the fibre fraction AFTER separation Calculation: Amount in Fibre fraction * 1000 / 228.58 kg	Composition of liquid fraction AFTER separation Calculation: Amount in Liquid fraction * 1000 kg / 771.42 kg
	[per 1000 kg ex pre-tank]		[per 1000 kg ex pre-tank]	[per 1000 kg ex pre-tank]	[kg per 1000 kg fibre fraction]	[kg per 1000 kg liquid fraction]
Total mass	1000 kg Slurry Ex pre-tank	22.858%	228.58 kg	1000 kg – 228.58 kg = 771.42 kg	1000 kg Fibre fraction	1000 kg liquid fraction
Dry matter (DM)	69.7 kg	87.2%	69.7 kg *87.2% = 60.778 kg	69.7 kg *(100-87.2)% = 8.922 kg	265.9 kg	11.57 kg
Total-N	5.48 kg	41.9%	5.48 kg *41.9% = 2.296 kg	5.48 kg *(100-41.9)% = 3.1839 kg	10.045 kg	4.127 kg
NH4-N	4.11 kg[a)]	16.7%	4.11 kg *16.7% = 0.6864 kg	4.11 kg *(100-16.7)% = 3.4236 kg	3.00 kg	4.438 kg
Total-P	1.13 kg	90%	1.13 kg *90% = 1.017 kg	1.13 kg *(100-90)% = 0.113 kg	4.449 kg	0.1465 kg
Potassium (K)	2.85 kg	14.2%	2.85 kg *14.2% = 0.4047 kg	2.85 kg *(100-14.2)% = 2.4453 kg	1.77 kg	3.17 kg
Carbon (C)	33.3 kg	87.2%	33.3 kg *87.2% = 29.04 kg	33.3 kg *(100-87.2)% = 4.26 kg	127.05 kg	5.522 kg
Copper (Cu)	30.0 g	36.2%	0.030 kg *36.2% = 0.01086 kg	0.030 kg *(100-36.2)% = 0.01914 kg	0.0475 kg	0.0248 kg
Zinc (Zn)	89.4 g	42.2%	0.0894 kg *42.2% = 0.0377 kg	0.0894 kg *(100-42.2)% = 0.0517 kg	0.1649 kg	0.0670 kg

a) Assumed to be 75 % of the total N, as in Annex A (table A.1, footnote c)

The composition of the slurry used in order to get the experimental data presented in table F.4 is presented in table F.7 and is compared to the slurry used in this study (i.e. slurry from the Norm data, as described in Annex A and detailed in table A.1. of Annex A). The resulting composition of both fractions are also compared and discussed. This comparison is performed since most of the separation efficiencies used in this project come from the experimental data provided by GEA.

Table F.7
Comparison of the separation of the “Danish Norm Data pig slurry” with the pig slurry sample used by gea for measurements.

	Norm Data pig slurry BEFORE separation	GEA pig slurry sample BEFORE separation	Norm Data FIBER fraction	GEA slurry sample FIBER fraction	Norm Data LIQUID fraction	GEA pig slurry sample LIQUID fraction
	[per 1000 kg slurry]	[per 1000 kg slurry]	[per 1000 kg fibre fraction]	[per 1000 kg fibre fraction]	[per 1000 kg liquid fraction]	[per 1000 kg liquid fraction]
Total mass distribution	100%	100%	22.86%	14.3-20.0%	77.14%	80-83.6%
Dry matter (DM)	69.7 kg	44.6 kg	265.9 kg	265.9 kg	11.57 kg	7.6%
Total-N	5.48 kg	3.91 kg	10.045 kg	10.03 kg	4.127 kg	2.38 kg
NH4-N	4.11 kg (= 75% of tot-N)	2.19 kg (~ 56% of tot-N)	3.00 kg	2.24 kg	4.438 kg	2.30 kg
Total-P	1.13 kg	0.60 kg	4.449 kg	3.67 kg	0.1465 kg	0.07 kg
Potassium (K)	2.85 kg	1.61 kg	1.77 kg	1.40 kg	3.17 kg	1.47 kg

When comparing the separation of the “Norm Data pig slurry” and the “GEA pig slurry sample” in table F.7, it can be seen that:

- The GEA pig slurry sample is in general more diluted than the Norm Data pig slurry BEFORE the separation. It contains relatively more water.
- It should be noted that the GEA pig slurry sample has a significantly low NH4-N content compared to the total N content (only 56% of the total N is NH4-N which is low compared to the “typical” 75% in the Norm Data).
- The Norm Data fibre fraction after the separation is close to having the same composition as the GEA pig slurry sample (except for the NH4-N and Org-N). It means that the fibre fraction is “realistic”.
- The liquid fraction from the GEA pig slurry data is in general more diluted than the liquid fraction from the Norm Data pig slurry. It reflects the difference of water content between the slurries before the separation.

F.4.3 Polymer addition

As described in F.4.1, the GEA separation includes the use of a polymer (liquefied cationic polyacrylamide). The polymer data is shown in table F.8 below.

Table F.8.
Data on the polymer used for the separation.

Polymer consumption	
Mass of polymer consumed (cationic polyacrylamide)	0.90 kg per 1000 kg slurry input in the separation process
Polymer commercial name	
Optifloc® C-2364 flocculant	
Polymer composition	
Citric acid	3%[a)]
Unspecified mineral oil distillate (acrylamide)	25% [a)]
Ethoxylated alcohols (C12-16)	4% [a)]
Water	68% [b)]

a) From the “Sikkerhedsdatablad”
b) Calculated as the rest

Polyacrylamide polymers (PAM) are widely investigated in the scientific literature as regarding their performance in solid-liquid separation of slurries (e.g. Martinez-Almela and Barrera, 2005; Campos et al., 2008; Vanotti et al., 2002; Vanotti et al., 2005; González-Fernández et al., 2008; Hjorth et al., 2008). Though the polyacrylamide polymer can be defined as many units of the monomer acrylamide, the chemical nature of the polymer and the monomer is highly different (Caulfield et al., 2002). While polyacrylamide is considered as a relatively safe material, the toxicity of acrylamide monomer is a major concern (El-Mamouni et al., 2002), this component being known to affect the central and peripheral nervous system (ICON, 2001). PAM can be charged positively (anionic), negatively (cationic) or non-charged (non-ionic) (Barvenik, 1994). Concerns regarding the toxicity of cationic PAM (as used in this project) have been expressed in the literature (e.g. Entry et al., 2002; Barvenik, 1994), and flow-through conditions showed that water-soluble cationic polymers present more long-term toxicity than they do under static conditions (Goodrich et al., 1991).

Once the PAM degrades to acrylamide monomer, the monomer is then subjected to rapid degradation in which it is decomposed to ammonia and to acrylic acid ($CH_2CHCOOH$), which in turn is degraded to CO_2 and water (ICON, 2001). Because of the extremely rapid degradation of the acrylamide monomer, it is reported that it is unlikely to find this toxic product in the environment as a result of PAM degradation (Sojka et al., 2007).

Campos et al. (2005) investigated if PAM degradation takes place during the anaerobic digestion of solid fractions obtained from pig slurry separated with and without the use of PAM. The authors concluded from the results of their biodegradability study that PAM is not significantly biodegradable by anaerobic microorganisms and is not toxic for anaerobic microorganisms, as no significant differences were observed between the maximum methanogenic activity of the different treatments investigated (different concentration of PAM in the solid fractions). Similarly, Martinez-Almela and Barrera (2005) as well as Gonzalez-Fernández et al. (2008) also concluded that PAM residues do not contribute to toxicity of the anaerobic digestion and do not affect the methane production. Recalcitrance of PAM to microbial degradation under both aerobic and anaerobic conditions was also observed by El-Mamouni et al. (2002).

In this study, it was therefore considered that all the polymer used during the separation will end up in the field, through the application of the degassed fibre fraction as a fertilizer. The fate of the polymer in the soil is further detailed in section F.23.

F.4.4 Energy consumption

The electricity consumption for the separation is calculated based on data from Frandsen (2009). According to this, the energy consumption for separating pig slurry with a GEA separator requires 2.45 kWh per m^3 when separating 5 m^3 slurry per hour and 1.86 kWh per m^3 slurry when separating 7 m^3 slurry per hour. According to the GEA measurements including addition of polymer used in this Annex, 5.5 $m^3$of slurry was separated per hour, corresponding to approximately 2.3 kWh per m^3 slurry (using linear interpolation). Using a slurry density of 1053 kg per m^3 for pig slurry (from

Annex A, table A.1), this means that 2.184 kWh are needed per 1000 kg of slurry input in the separator, as presented in table F.9.

Table F.9.
Energy consumption for the separation process

Energy consumption	
Electricity needed for separation	2.184 kWh per 1000 kg slurry input

F.4.5 Material consumption

A list of the materials used for the construction of the separation equipment is shown in table F.10. This material consumption is based on qualified expert estimates and was assumed to be of the same magnitude as for the mechanical separation in Annex C. As calculations performed by Wesnæs et al. (2009) has shown that the material consumption has no significance for the overall environmental impacts, the differences between the separator in this Annex and the separator in Annex C has no significance.

Table F.10
Material consumption for the separation equipment

Materials	Weight of material in plant	Estimated life time	Amount of slurry per year [m^3 slurry per year]	Amount of slurry in a life time [m^3 slurry in a life time]	Weight [per 1000 kg slurry]
Separator					
Steel in container	2 300 kg	30 years	15000 m^3 / y	450000 m^3	5 g
Steel in compressor	2 700 kg	30 years	15000 m^3 / y	450000 m^3	6 g
Copper in cables	10.5 kg	30 years	15000 m^3 / y	450000 m^3	0.023 g
Electronics	0.5 kg - Assumed as 0.5 laptops	Assumption: 5 years	15000 m^3 / y	75000 m^3	6.67 E-6 laptops
Screw in screw press					
Steel	50 kg	1 years	15000 m^3 / y	15000 m^3	3.3 g
Filter for screw press					
Steel	6.5 kg	0.5 year	15000 m^3 / y	7500 m^3	0.86 g

F.4.6 Overall life cycle data for separation

Table F.11 presents the overall lifecycle data for the separation process. It should be highlighted that no data as regarding the emissions occurring during the separation process has been found. This lack of data is particularly critical as regarding ammonia emissions, which are likely to occur given the volatile nature of ammonia. Emissions of ammonia at this stage would change the total N content of the two fractions. As no data were available to make any reasonable estimate, no emissions will be considered to occur during the separation. Yet, it appears reasonable to assume that all the emissions likely to occur during the separation are occurring in later stages anyway, so considering them at this stage or at later stages does not change the overall results.

Table F.11.
Life cycle data for separation (decanter centrifuge + polymer). Data per 1000 kg slurry (ex pre-tank).

	Fattening pig slurry	Comments
Input		
Slurry (ex pre-tank)	1000 kg	Slurry directly from the pre-tank. This is the reference amount of slurry, i.e. the emissions are calculated relative to this.
Output		
Fibre fraction	222.58 kg	
Liquid fraction	771.42 kg	
Energy consumption		
Electricity	2.184 kWh	See table F.9
Material consumption		
Separation equipment	included	See table F.10
Consumption of chemicals		
Polymer added during the separation	0.90 kg	Polymer composition detailed in table F.8.
Emissions to air		
Carbon dioxide (CO_2)		No data
Methane (CH_4)		No data
Non-methane volatile organic compounds (NMVOC)		No data
Ammonia (NH_3-N)		No data.
Nitrous oxide (N_2O-N)		No data
Nitrogen oxides (NO_X)		No data
Nitrogen monoxide(NO)		No data
Nitrogen(N_2)		No data
Particulates		No data
Hydrogen sulphide (H_2S)		No data
Sulphur dioxide (SO_2)		No data
Odour		No data
Emissions to water		
		No emissions to water

F.5 Outdoor storage of the liquid fraction

F.5.1 General description

The liquid fraction is stored in an outdoor concrete tank covered with a floating layer consisting of 2.5 kg of straw per 1000 kg slurry stored (as in the outdoor storage of the untreated slurry in the reference scenario, Annex A). Because straw is regarded as a waste product from cereal production (rather than a co-product), the life cycle data of straw production are not included in this study.

F.5.2 Addition of water

Water will be added in the liquid fraction during storage through precipitations. The amount of precipitations is the same as in Annex A, i.e. a total of 86 kg of water.

F.5.3 Electricity consumption

The electricity for pumping and stirring is taken from table A.10 (Annex A) and further adjusted by a reduction factor. This is because the electricity consumption data presented in Annex A are for raw slurry. Yet, the separated liquid fraction can be anticipated to offer much less resistance when stirring or pumping than does the slurry, therefore resulting in smaller energy consumption. Therefore, the total energy consumption, as calculated from data in Annex A, will be multiplied by 0.5. This is a rather rough estimate, but as the energy consumption from pumping and stirring has had a rather insignificant contribution on the overall environmental impacts in Wesnæs et al. (2009) (figure 3.3), the magnitude of the uncertainty does not matter so much for this parameter.

The electricity consumption involves : the consumption for stirring when straw is added (1.2 kWh per 1000 kg slurry), the consumption for stirring (1.2 kWh per 1000 kg) and pumping (0.5 kWh per 1000 kg slurry), before application to the field. This gives an electricity consumption of 2.9 kWh per 1000 kg slurry, on which a factor of 50 % is applied, which results in an electricity consumption of 1.45 kWh per 1000 kg liquid fraction.

F.5.4 Emissions of CH_4

Martinez et al. (2003) studied the influence of different pig slurry treatment on the emissions occurring during storage. For the liquid fraction from slurry separation, they observed CH_4 emissions reduction of 7 % and 40 %, with laboratory scale and farm scale mechanical separator, respectively. The reductions are as compared to the emissions occurring during the storage of non treated pig slurry. They measured emissions of CH_4-C corresponding to 1.9 % and 10.2 % of the initial C, for the two different separation technologies tested after 50 days of open storage. Dinuccio et al. (2008) measured CH_4-C emissions from a mechanically separated liquid fraction (from raw swine slurry) corresponding to 4.39 and 12.8 % of the VS for slurry stored during 30 d at 5 °C and 25 °C respectively.

For this project, it has been decided to calculate the CH_4 emissions based on the IPCC methodology[5], but by using the VS content of the separated liquid fraction (the VS being calculated with the hypothesis that VS = DM * 80 %). This gives a CH_4 emission of 0.279 kg per 1000 kg of liquid separated fraction (i.e. 80 % * 11.57 kg DM per 1000 kg liquid fraction * 0.45 * 0.67 * 10 % = 0.279 kg).

This represents the highest emission potential, as not all the VS will contribute significantly to CH_4 emissions. In fact, the heavily degradable portion of the VS is recalcitrant to microbial degradation (Sommer et al., 2009). Yet, no information is available in the literature in order to assess the portion of easily and heavily degradable VS in both liquid and solid fractions

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[5] According to IPCC (2006), the methane emission can be calculated as:
CH_4 [kg] = VS [kg] * B_0 * 0.67 [kg CH_4 per m^3 CH_4] * MCF
The VS amount is “ex-animal” and B_0 = 0.45 m^3 CH_4 per kg VS for market swine (IPCC, 2006, Table 10A-7). The MCF value used is 10 % (for liquid slurry with natural crust cover, cool climate, in table 10-17 of IPCC (2006)). This is also the MCF recommended under Danish conditions by Nielsen et al. (2009).

of separated slurry (Sommer et al., 2009). This means that, with the actual status of data availability, it is not possible to reflect the better performance of some separation technologies as regarding their efficiency in separating the easily degradable VS in the solid fraction and heavily degradable VS in the liquid fraction. Separating the easily degradable VS out of the liquid fraction is desirable, given the anaerobic conditions of the liquid fraction favouring their degradation into CH_4 and CO_2.

The CH_4 emissions estimated in this project may therefore slightly overestimate the actual magnitude of emissions occurring during the storage of the separated liquid. On the other hand, the effect of the straw cover, which represents an additional C source for methanogens, was not accounted for, in conformity with the reference scenario. Therefore, it is assumed that these effects are overall counterbalanced and that the CH_4 emissions calculated as described above give a fair picture of the emissions occurring in reality.

The value of 0.279 kg CH_4 emissions per 1000 kg of liquid fraction used in this study represents a reduction of 86 % as compared to the emissions occurring during storage of raw slurry (which was 1.94 kg CH_4 per 1000 kg slurry ex-housing, table A.11, Annex A), which is quite higher than the reductions reported in the literature. This is due to the better separation efficiency of total VS of the separation technology used in this study.

F.5.5 Emissions of CO_2

Emissions of CO_2 were estimated as a function of the methane emissions. This is the approach used throughout this study for estimating CO_2 emissions in processes where slurry is kept in anaerobic conditions (e.g. F.5 and F.25)

The ratio between CO_2 and CH_4 emitted during anaerobic degradation was estimated based on the Buswell equation (Symons and Buswell, 1933), as presented in equation (1):

$$C_nH_aO_b + \left(n - \frac{a}{4} - \frac{b}{2}\right) H_2O \rightarrow \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right) CH_4 + \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4}\right) CO_2 \quad (1)$$

The organic components making up the VS in slurry and their relative amount in pig slurry were taken from Sommer et al. (2009), and are presented in table F.12.

Table F.12
Organic components constituting the VS in slurry and their relative amount in pig slurry (adapted from Sommer et al., 2009).

Organic component	Formula	Relative amount in pig slurry (%)
VS easily degradable		
VS lipid	$C_{57}H_{104}O_6$	16.2
VS protein	$C_5H_7O_2N$	27.0
VS VFA	$C_2H_4O_2$	8.5
VS carbohydrates easily degradable	$C_6H_{10}O_5$	27.1
VS heavily degradable		
VS carbohydrates heavily degradable	$C_6H_{10}O_5$	21.2
TOTAL		100

Based on equation (1) and table F.12, the ratio between the number of moles of CO_2 and CH_4 from the full degradation of the easily degradable VS in the slurry can be calculated, as presented in table F.13.

Table F.13
Calculation of the ratio between the number of moles of CO_2 versus CH_4 resulting from the degradation of the easily degradable VS in the pig slurry

Organic component	Unit	CH_4	CO_2
VS lipid (1 mol)	[moles of CH_4 and CO_2 from the degradation of 1 mol VS lipid]	40 moles	17 moles
	[weight for VS lipid in pig slurry, table F.12]	16.2 %	16.2 %
	[moles of CH_4 and CO_2 from the degradation of 1 mol VS lipid as weighted for the pig slurry]	6.48 moles	2.75 moles
VS protein (1 mol)	[moles of CH_4 and CO_2 from the degradation of 1 mol VS protein]	2.9 moles	2.1 moles
	[weight for VS protein in pig slurry, table F.12]	27.0 %	27.0 %
	[moles of CH_4 and CO_2 from the degradation of 1 mol VS protein as weighted for the pig slurry]	0.78 moles	0.57 moles
VS VFA (1 mol)	[moles of CH_4 and CO_2 from the degradation of 1 mol VS VFA]	1 mole	1 mole
	[weight for VS VFA in pig slurry, table F.12]	8.5 %	8.5 %
	[moles of CH_4 and CO_2 from the degradation of 1 mol VS VFA as weighted for the pig slurry]	0.09 moles	0.09 moles
VS carbohydrates easily degradable (1 mol)	[moles of CH_4 and CO_2 from the degradation of 1 mol VS carbohydrates easily degradable]	3 moles	3 moles
	[weight for VS carbohydrates easily degradable in pig slurry, table F.12]	27.1 %	27.1 %
	[moles of CH_4 and CO_2 from the degradation of 1 mol VS carbohydrates easily degradable as weighted for the pig slurry]	0.81 moles	0.81 moles
SUM (moles of CH_4 and CO_2 as weighted for the pig slurry)		8.16 moles	4.22 moles
Ratio CO_2/CH_4		0.52 moles CO_2 per mole CH_4	

The ratio of 0.52 moles of CO_2 per mole of CH_4 calculated in table F.13 means that an amount of 1.42 g of CO_2 is produced per g of CH_4[6]. This estimate will be used in order to estimate the CO_2 emissions from the various slurry types involved in this study when slurry is kept in anaerobic conditions.

As mentioned in section F.2, part of the produced CO_2 from the outdoor storage is emitted to air immediately and part of the CO_2 is dissolved in the slurry. However, in this life cycle assessment, it is calculated as all the CO_2 is emitted to air immediately, which makes the interpretation of the sources easier, as detailed in section F.2.

F.5.6 Emissions of NH_3

In this project, the ammonia emissions are calculated using the same assumption as for the reference scenario: According to Poulsen et al. (2001),

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[6] Calculated as: (0.52 moles CO_2/mole CH_4) * (1 mole CH_4/16.043 g CH_4) * (44.099 g CO_2/mole CO_2) = 1.42 g CO_2/g CH_4.

the emission of NH_3–N is 2% of the total-N in the slurry "ex housing" (i.e. "ex separation" in the present case). This corresponds to NH_3–N emissions of 0.0825 kg per 1000 kg of separated liquid.

F.5.7 Emissions of N_2O-N, NO-N and N_2-N

In the reference scenario, the direct N_2O-N emissions for storage were based on IPCC guidelines (IPCC, 2006). However, the IPCC methodology does not provide any emission factor for storage of separated liquid fraction. Accordingly, the direct N_2O emissions were estimated relative to the emissions in the reference scenario, adjusted with the different N content. The content of total-N "ex separation" is 4.127 kg/1000 kg liquid fraction (table F.6). The content of total-N in the reference slurry is 5.48 kg per 1000 kg slurry ex-housing (table A.1, Annex A). The direct N_2O emissions in the reference scenario were 0.033 kg N_2O-N per 1000 kg slurry ex-housing (table A.11, Annex A). Therefore, the direct N_2O-N emissions are calculated as: 0.033 kg N_2O-N * (4.127/ 5.48) = 0.0249 kg N_2O-N per 1000 kg liquid fraction. This is also a rough estimate. Yet, it is acknowledged that the N_2O emissions may in fact be lower than this estimate due to the lower DM content in the liquid fraction (and thereby a lower potential for easily converted VS content).

The NO-N and N_2-N emissions were calculated in the same way as in Annex A, i.e. based on the study of Dämmgen and Hutchings (2008). In their study, they assumed that the emission of nitrogen monoxide (NO) is the same as the direct emission of nitrous oxide (N_2O) (measured as NO-N and N_2O-N). Furthermore, they assumed that emission of nitrogen (N_2) is three times as high as the direct emissions of nitrous oxide (N_2O) (measured as N_2-N and N_2O-N).

As regarding the total NO_X emissions (NO_X = NO + NO_2), it was assumed, as in Annex A, that NO_X = NO. This is because it has not been possible to find data on NO_2.

Therefore, this means that the NO-N emissions (and thereby the NO_X-N emissions) correspond to 0.0249 kg per 1000 kg liquid fraction and the N_2-N emissions correspond to 0.0747 kg per 1000 kg liquid fraction.

The indirect N_2O-N emissions can be calculated as described by IPCC guidelines (IPCC, 2006), i.e. as 0.01 * (NH_3-N + NO_X-N). This gives indirect N_2O-N emissions of 0.00107 kg per 1000 kg liquid fraction.

F.5.8 Life cycle data and mass balances for storage of liquid fraction

Table F.14 summarizes the LCA data for the storage of liquid fraction and presents the comparison with the storage emissions in Annex A. It must be emphasized that 1000 kg liquid fraction do ***not*** correspond to 1000 kg slurry ex animal, so the values of Annex A versus Annex F are not directly comparable. Values from Annex A were only included since they were needed for the calculation of some of the emissions. For CO_2, values from Annex A are presented as they were calculated, and their equivalent is presented in parenthesis if they would have been calculated according to the ratio between CH_4 and CO_2, as explained in section F.5.5.

Table F.15 presents the mass balance of the liquid fraction in order to establish its composition after the storage. In this table, it can be noticed that the change of DM is estimated as the losses of N and C. It is acknowledged that this is a rough estimation, as other elements of greater molecular weight may also be lost (e.g. dissolved O_2). The estimated DM change shall therefore be seen as a minimum change, the actual DM change may in fact be greater than the one taken into account in this study.

Table F.14
Life cycle data for storage of the liquid fraction. All data per 1000 kg of liquid fraction “ex separation”.

	Reference pig slurry (scenario A)	Liquid fraction (fattening pig slurry) (scenario H)	Comments
Input			
Liquid fraction “ex separation”		1000 kg	The emissions are calculated relative to this.
Slurry “ex housing”	1000 kg		
Water	86 kg	86 kg	
Concrete slurry store	Included	Included	As in scenario A.
Cut straw	2.5 kg	2.5 kg	As straw is regarded as a waste product from cereal production (rather than a co-product), the life cycle data of straw production are not included.
Output			
Slurry “ex storage”	1086 kg	1086 kg	
Energy consumption			
Electricity		1.45 kWh	Electricity for pumping and stirring (see text).
Emissions to air			
Carbon dioxide (CO_2)	0.18 kg (if calculated as in Annex F :2.75 kg)	0.396 kg	Calculated from CH_4 emissions: kg CO_2 = kg CH_4 * 1.42 (see text).
Methane (CH_4)	1.94 kg	0.279 kg	Based on IPCC methodology (IPCC, 2006), but with VS of separated liquid fraction, see text.
Ammonia (NH_3-N)	0.11 kg	0.0825 kg	NH_3-N = 2% of the total N in the liquid fraction “ex-separation”, see text.
Direct emissions of Nitrous oxide (N_2O-N)	0.033 kg	0.0249 kg	Evaluated based on reference slurry emissions, adjusted with relative total N ratios (see text).
Indirect emissions of Nitrous oxide (N_2O-N)	0.0014 kg	0.00107 kg	0.01 kg N_2O–N per kg (NH_3–N + NO_X–N) volatilised (IPCC, 2006, table 11.3), see text.
Nitrogen monoxide (NO-N) (representing total NO_X)	0.033 kg	0.0249 kg	Estimate based on Dämmgen and Hutchings (2008), consisting of assuming that NO-N = (direct) N_2O-N * 1, see text.
Nitrogen dioxide (NO_2-N)	No data	No data	No data
Nitrogen (N_2-N)	0.099 kg	0.0747 kg	Estimate based on Dämmgen and Hutchings (2008), consisting of assuming that N_2-N = (direct) N_2O-N * 3
Discharges to soil and water			
	None	None	Assumed to be none, as leakages from slurry tanks are prohibited in Denmark

Table F.15.
Mass balances for storage of liquid fraction after separation

	Composition of liquid fraction AFTER separation and BEFORE storage (from table F.6) [kg per 1000 kg liquid fraction]	Mass balance: Change during storage of liquid fraction [kg]	Mass balance: Amount after storage of liquid fraction [kg]	Composition of liquid fraction AFTER storage [kg per 1000 kg liquid fraction AFTER storage]
Total mass	1000 kg	86 kg	1086 kg	1000 kg
Dry matter (DM)	11.57 kg	- 0.524 kg [c)]	11.05 kg	10.17 kg
Total-N	4.127 kg	- 0.207 kg [a)]	3.92 kg	3.61 kg
Total-P	0.1465 kg	No change	0.1465 kg	0.135 kg
Potassium (K)	3.17 kg	No change	3.17 kg	2.92 kg
Carbon (C)	5.525 kg	- 0.317 kg [b)]	5.21 kg	4.80 kg
Copper (Cu)	0.0248 kg	No change	0.0248 kg	0.0228 kg
Zinc (Zn)	0.0670 kg	No change	0.0670 kg	0.0617 kg

[a] Changes in total N: 0.0825 kg NH_3-N + 0.0249 kg N_2O-N + 0.0249 kg NO-N + 0.0747 kg N_2-N = 0.207 kg N

[b] Changes in total C: 0.396 kg CO2 * 12.011 [g/mol] /44.01 [g/mol] + 0.279 kg CH4 * 12.011 [g/mol] /16.04 [g/mol] = 0.317 kg C

[c] The change in DM is assumed to be identical to the sum of the loss of N and C

F.6 Transport of the liquid fraction to the field

The transport of the liquid fraction to field is assumed to be identical to the transport of the untreated slurry in Annex A. Accordingly, the same assumptions have been applied.

This means that the process “Transport, tractor and trailer” from the Ecoinvent database (Nemecek and Kägi, 2007, p.204) has been used, for a distance of 10 km. This includes the construction of the tractor and the trailer. As the transport by trucks (instead of by tractor with a trailer) is required by law in Denmark when the slurry is transported for distances greater than 10 km, Wesnæs et al. (2009) carried out a sensitivity analysis with a transportation distance of 32 km (involving transport by truck). Yet, they found that the transport distance of slurry from the storage to the field had no significance on the environmental impacts they assessed. Therefore, the transport distance from storage to field is fixed to 10 km in the present project.

F.7 Field processes (liquid fraction)

F.7.1 General description

As in Annex A, the data from the Ecoinvent process “Slurry spreading, by vacuum tanker” (Nemecek and Kägi, 2007, p.198) were used for the emissions related to spreading equipment “consumption”. This includes the construction of the tractor and the slurry tanker, as well as the diesel consumption. The diesel consumption due to the use of the “tanker” in the Ecoinvent process was adjusted to 0.4 litres of diesel per 1000 kg of slurry, based on Kjelddal (2009) (the same as in Annex A).

F.7.2 Emissions of CH_4 and CO_2

The CH_4 emissions on the field are assumed to be negligible, as the formation of CH_4 requires an anaerobic environment, which is, under normal conditions, not the case in the top soil.

CO_2 emissions and C-binding in the soil are modelled by the dynamic soil organic matter model C-TOOL (Petersen et al., 2002; Gyldenkærne et al., 2007). The development in organic soil N is modelled by assuming a 10:1 ratio in the C to N development.

F.7.3 Emissions of NH_3-N

The NH_3-N emissions ***during application*** were calculated as in the reference scenario, i.e. 0.5 % of the NH_4^+-N "ex-storage". This is based on Hansen et al. (2008). Yet, Hansen et al. (2008) calculated NH_4^+-N "ex-storage" as 79 % of the total N (instead of 75 % as assumed in this study). In this specific case, because the NH_3-N emissions are calculated based on Hansen et al. (2008), the NH_4^+-N will be evaluated with the figures presented by Hansen et al. (2008), as it was done in Annex A.

According to Hansen et al. (2008), the ammonia volatilization from the liquid fraction from separated slurry applied to fields is reduced significantly in the period ***after application*** – in the order of 50%. The explanation given by Hansen et al. (2008) is that the dry matter in the liquid fraction is normally less than 3% which means that the liquid fraction infiltrates very fast in the soil, so less ammonia is likely to volatilize as compared to untreated slurry. Measurements were made on mechanically separated slurry (untreated and degassed slurry), and the liquid fraction and control slurry were applied by trail hoses. The measurements showed that the ammonia emissions were reduced by approximately 50% (Hansen et al., 2008) for the liquid fraction. Accordingly, a reduction of 50 % was used for ammonia emissions (after application) in this project, as compared to the ammonia emissions occurring in the reference scenario. Consequently, the emissions were first calculated with the methodology presented in Annex A (section A.5.3) and the result of this was multiplied by 50 %.

In Annex A, an area and slurry-N weighted average of all the NH_3-N losses involved in the crop rotation defined for the "pig slurry" scenario was performed. This resulted in a loss of 0.138 kg NH_3-N per kg TAN-N in the pig slurry (a loss that includes the emissions during application, so they have to be deduced). Assuming that the TAN (NH_3+NH_4^+), at the liquid fraction pH, corresponds to NH_4^+ only, and evaluating NH_4^+-N as 79 % of the total N (as this estimation is also based on the study of Hansen et al., 2008), it is possible to estimate the NH_3-N emissions after application.

F.7.4 Emissions of N_2O-N and NO_X-N and N_2-N

Direct and indirect N_2O-N emissions as well as emissions of NO_X-N were calculated as in the reference scenario (section A.5.3 and A.5.4 in Annex A). This means that the direct emissions of N_2O-N are evaluated as 0.01 kg N_2O-N per kg N in the ex-storage liquid fraction (table 11.1 in IPCC (2006)). Yet, it is acknowledged that this may overestimate the N_2O emissions occurring from the spreading of the liquid fraction, as the C/N ratio of the liquid fraction is lower than the C/N ratio of the non-separated slurry. In fact, according to Møller et al. (2007c), the centrifugal separation mainly transfers the organic N to the solid fraction, while the dissolved NH_4^+ goes in the liquid fraction. A higher NH_4-N content involves more N in a form directly available for plants. This means that less N shall be available to microorganisms for nitrification (where NO_3^- is formed), and thus, the potential for denitrification (where NO_3^- is reduced to N_2O, and subsequently to N_2) is reduced. According to Amon et al. (2006), a lower C/N ratio also reduces the potential for N immobilisation in the soil N pool, and thereby the availability of N for denitrification.

The indirect N_2O-N emissions ***due to ammonia and NO$_x$*** are evaluated as 0.01 kg N_2O-N per kg of (NH_3 + NO_X) volatilized. The indirect N_2O-N emissions ***due to nitrate leaching*** correspond to 0.0075 kg N_2O-N per kg of N leaching.

The emissions of NO_X-N are calculated as 0.1* direct N_2O-N, based on Nemecek and Kägi (2007).

The N_2-N emissions are based on the estimates from SimDen (Vinther, 2004). For soil type JB3 the N_2-N:N_2O-N ratio is 3:1 and for soil type JB6 the N_2-N:N_2O-N ratio is 6:1.

F.7.5 Calculation of liquid fraction fertilizer value

The calculation of the liquid fraction fertilizer value is presented and detailed in section F.28.

F.7.6 Nitrate leaching

In order to calculate N leaching values, the same simplifying assumption as in Annex C is used: the liquid fraction, once the respective ammonia losses have been subtracted, can be modeled as: a given proportion of slurry + a given amount of mineral N. The present liquid fraction has a higher content of N relative to C, as compared to the original reference slurry. This is because the mechanical separation transfers relatively more C to the fibre fraction than N. As the amount of organic matter is one of the key properties for its effect on the N partitioning, the amount of C relative to N in the pig slurry from the reference scenario is used. The N values are taken after ammonia volatilization. The C:N proportion is 29.2 [kg C] / (4.80-0.02-0.48) [kg N] = 6.79 for the slurry and 4.8 [kg C] / (3.61-0.02-0.19) [kg N] = 1.41 for the liquid fraction. The “virtual” proportion of N assumed to affect the soil and plants as raw slurry is therefore 1.41/6.79 = 0.21, and the virtual proportion of N assumed to affect the soil and plants as mineral N is accordingly 0.79. The tables A.14 and A.15 of Annex A are therefore the basis for the calculation of N leaching, after correcting for their respective ammonia volatilization.

F.7.7 Phosphorus leaching

For P leaching, the same assumptions as those used in Annex A were used, i.e., 10% of the P applied to field has the possibility of leaching and 6% of this actually reach the aquatic recipients, based on Hauschild and Potting (2005).

F.7.8 Cu and Zn fate

As in Annex A, it is considered that the entirety of the Cu and Zn applied will leach through the water compartment.

F.7.9 Life cycle data for field application of liquid fraction

Table F.16 presents the life cycle data for the application of ex-storage liquid fraction on the field. The results of the reference case (Annex A) are also presented for comparison purposes. However, in order to be comparable, both results must be related to the functional unit, i.e. 1000 kg slurry ex-animal.

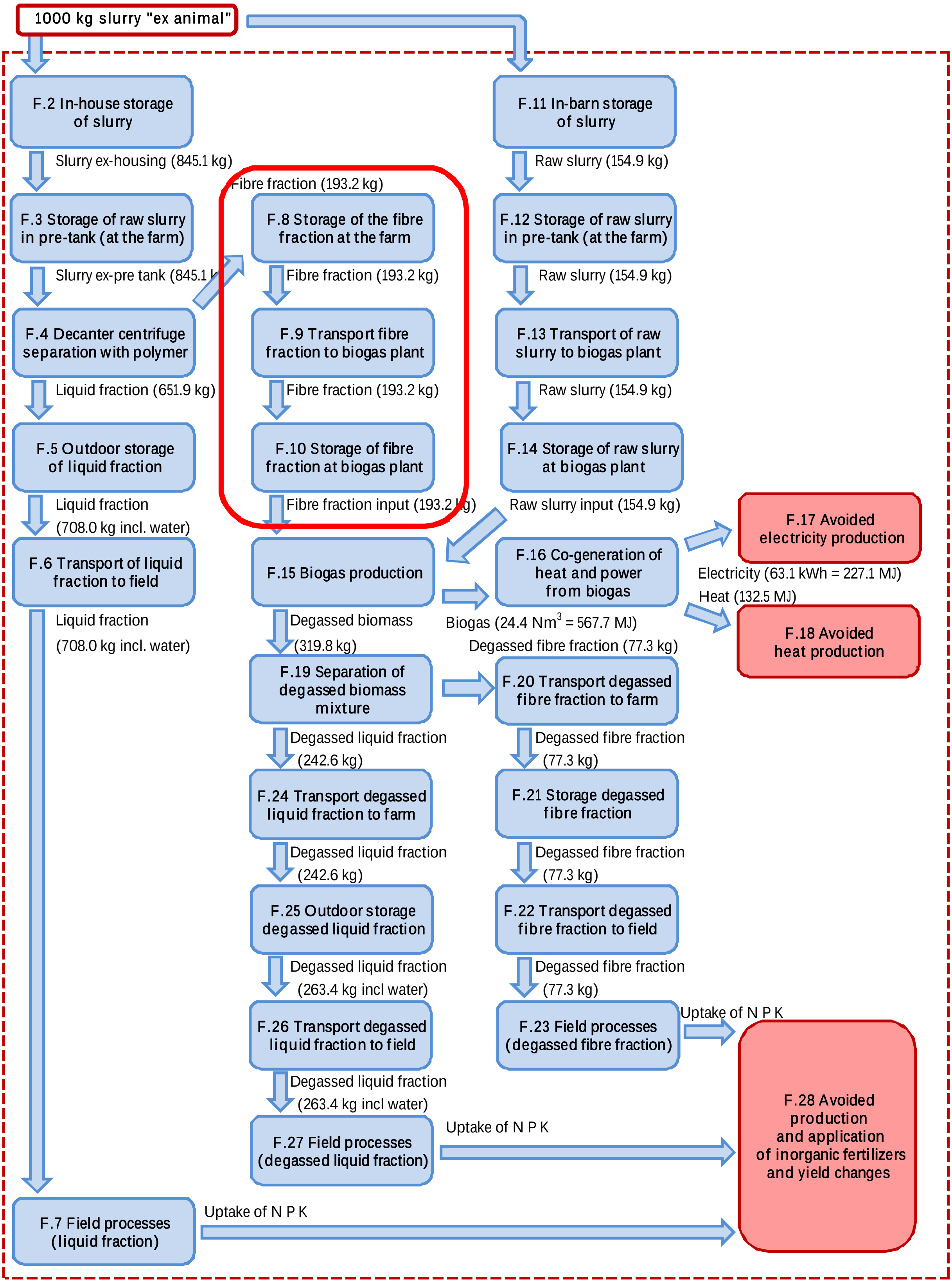
Table F.16.
Life cycle data for the field processes related with the application of liquid fraction. All data per 1000 kg of “liquid fraction ex-storage”.

	Fattening pig slurry (Annex A)	Liquid fraction after storage (Annex F)	Comments
Input			
Slurry/ liquid fraction “ex- storage”	1000 kg	1000 kg	Slurry / liquid fraction from the outdoor storage.
Output			
Slurry on field, fertiliser value	Fertiliser replacement value: 3.75 kg N 1.04 kg P 2.6 kg K	Fertiliser replacement value, N, P and K: see section F.28.	
Energy consumption			
Diesel for slurry	0.4 litres of diesel	0.4 litres of diesel	See Annex A, section A.5.1.
Emissions to air			
Carbon dioxide (CO_2) Soil JB3 Soil JB6	 81.6 kg (99.8 kg) 80.2 kg (99.4 kg)	 3.9 (13.7) kg 3.7 (13.7) kg	Modelled by C-TOOL (Gyldenkærne et al, 2007). 10 year value shown, 100 years value in parenthesis.
Methane (CH_4)	Negligible	Negligible	The CH_4 emission on the field are assumed to be negligible, as the formation of CH_4 requires anoxic environment (the field is aerobic) (Sherlock et al., 2002).
Ammonia (NH_3-N) during application	0.02 kg	0.0143 kg	NH3 emissions during application: 0.5% of NH4+-N “ex-storage”, the NH4+-N “ex-storage” being evaluated as 79 % of total N. Calculation based on Hansen et al. (2008), see text. 3.61 kg N * 79% * 0.5% = 0.0143 kg NH_3-N
Ammonia (NH_3-N) in period after application	0.48 kg	0.1896 kg	Correspond to 50 % of the emissions calculated as in Annex A. In Annex A, it is considered that there is a loss of 0.138 kg NH_3-N per kg of NH4-N (including losses of NH_3-N during application). NH4+-N is here evaluated as 79 % of total N. 50% * [0.138 kg NH_3-N/kg TAN * 79% * 3.61 kg N – 0.0143 kg NH_3-N during application] = 0.1896 kg NH_3-N.
Direct emissions of Nitrous oxide (N_2O-N)	0.05 kg [0.015-0.15]	0.0361 kg [0.0108-0.108]	0.01 [0.003 - 0.03] kg N_2O-N per kg N “ex-storage” for application of animal wastes to soil, based on IPPC (IPCC, 2006: table 11.1).
Indirect emissions of Nitrous oxide (N_2O-N)	0.005 kg	0.0021 kg	Indirect emissions due to emissions of ammonia and NO_X: 0.01 kg N_2O–N per kg (NH_3–N + NO_X–N) volatilised (IPCC, 2006).
Soil JB3 Soil JB6	0.014 kg (0.016 kg) 0.011 kg (0.013 kg)	0.011 kg (0.012 kg) 0.008 kg (0.009 kg)	Indirect emissions due to nitrate leaching: 0.0075 kg N_2O–N per kg N leaching (IPCC, 2006). 10 year value shown, 100 years value in parenthesis.

Table F.16. (continuation)
Life cycle data for the field processes related with the application of liquid fraction. All data per 1000 kg of “liquid fraction ex-storage”.

	Fattening pig slurry (Annex A)	Liquid fraction after storage (Annex F)	Comments
Emissions to air			
Nitrogen oxides (NO_x-N)	0.005 kg	0.00361 kg	NO_X–N = 0.1 * direct N_2O-N according to Nemecek and Kägi (2007)
Nitrogen (N_2-N) Soil JB3 Soil JB6	 0.15 kg 0.30 kg	 0.1083 kg 0.2166 kg	Estimated from the SimDen model ratios between N_2-N and N_2O-N (see text): 3:1 for soil JB3 and 6:1 for soil JB6.
Discharges to soil			
Nitrate leaching Soil JB3 Soil JB6	 1.91 (2.12) kg N 1.50 (1.67) kg N	 1.45 (1.61) kg N 1.13 (1.21) kg N	See text
Phosphate leaching	0.104 kg P	0.0135 kg P	10 % of the P applied to field, see text.
Copper (Cu)	0.0276 kg	0.0228 kg	100 % of the Cu applied is assumed the leach
Zinc (Zn)	0.0824 kg	0.0617 kg	100 % of the Zn applied is assumed the leach

Processes F.8 to F.10: Handling the fibre fraction from the farm to the biogas plant before biogas is produced



1000 kg slurry "ex animal"

F.2 In-house storage of slurry

Slurry ex-housing (845.1 kg)

F.3 Storage of raw slurry in pre-tank (at the farm)

Slurry ex-pre tank (845.1 kg)

F.4 Decanter centrifuge separation with polymer

Liquid fraction (651.9 kg)

F.5 Outdoor storage of liquid fraction

Liquid fraction (708.0 kg incl. water)

F.6 Transport of liquid fraction to field

Liquid fraction (708.0 kg incl. water)

F.7 Field processes (liquid fraction)

Uptake of N P K

Fibre fraction (193.2 kg)

F.8 Storage of the fibre fraction at the farm

Fibre fraction (193.2 kg)

F.9 Transport fibre fraction to biogas plant

Fibre fraction (193.2 kg)

F.10 Storage of fibre fraction at biogas plant

Fibre fraction input (193.2 kg)

F.15 Biogas production

Degassed biomass (319.8 kg)

F.19 Separation of degassed biomass mixture

Degassed liquid fraction (242.6 kg)

F.24 Transport degassed liquid fraction to farm

Degassed liquid fraction (242.6 kg)

F.25 Outdoor storage degassed liquid fraction

Degassed liquid fraction (263.4 kg incl water)

F.26 Transport degassed liquid fraction to field

Degassed liquid fraction (263.4 kg incl water)

F.27 Field processes (degassed liquid fraction)

Uptake of N P K

F.11 In-barn storage of slurry

Raw slurry (154.9 kg)

F.12 Storage of raw slurry in pre-tank (at the farm)

Raw slurry (154.9 kg)

F.13 Transport of raw slurry to biogas plant

Raw slurry (154.9 kg)

F.14 Storage of raw slurry at biogas plant

Raw slurry input (154.9 kg)

F.16 Co-generation of heat and power from biogas

Biogas (24.4 Nm^3 = 567.7 MJ)

Degassed fibre fraction (77.3 kg)

F.20 Transport degassed fibre fraction to farm

Degassed fibre fraction (77.3 kg)

F.21 Storage degassed fibre fraction

Degassed fibre fraction (77.3 kg)

F.22 Transport degassed fibre fraction to field

Degassed fibre fraction (77.3 kg)

F.23 Field processes (degassed fibre fraction)

Uptake of N P K

F.17 Avoided electricity production

Electricity (63.1 kWh = 227.1 MJ)

Heat (132.5 MJ)

F.18 Avoided heat production

F.28 Avoided production and application of inorganic fertilizers and yield changes

F. 8 Storage of the fibre fraction at the farm

At the farm, the fibre fraction is stored in a covered concrete container (Rosager, 2009). The storage duration varies between 1 and 3 days, the maximum being approximately 7 days (Jensen, 2009).

It is here important to highlight that the fibre fraction is stored in a covered structure. In fact, covering has a major mitigation impact on composting activity and on production and emission of greenhouse gases and NH_3, as further discussed in section F.21.

The emissions occurring during the storage of the fibre fraction are highly variable and are dependent upon various parameters such as the chemical composition and structure of the fibre fraction, the temperature and the storage time (Hansen, 2009; Dinuccio et al., 2008). The porous structure of the fibrous fraction causes a potential for a higher N loss during the storage and handling phases, especially as ammonia, as compared to raw manure (Petersen and Sørensen, 2008). However, Jørgensen and Jensen (2009) found no major differences in the proportion of NH_4-N of total N when they compared samples of fibre fractions that underwent 2 to 8 weeks storage to fibre fractions samples that were taken directly from the separator. This was true for 6 of their 7 samples of stored fibre fractions. Their stored fibre fractions samples were issued from both close and open storage. One of the hypotheses formulated by the authors to explain the non-significantly different proportions of NH_4-N from stored and fresh fibre fractions is that the storage period was not long enough to influence the apparent composition of N in the solids.

Based on these findings as well as on information from biogas producers (Rosager, 2009), the emissions occurring during the temporal storage of the fibre fraction at the farm are considered as negligible. Because it is considered that no losses occurs during this 1 to 3 days storage, the fibre fraction after the storage has the same composition as at the outlet of the separator (as presented in table F.6).

It is acknowledged that this is an important assumption impacting the whole mass balances for all subsequent process. As such, it is not suitable to carry out a sensitivity analysis on this. Instead, the importance of this assumption is raised as a discussion point in the interpretation of the results.

The material consumption related to the storage facilities is as described in table F.15. This is based on the process “slurry store and processing” from the Ecoinvent database (Nemecek and Kägi, 2007, p.182), which is for a covered concrete tank with 300 m^3 capacity. It is estimated that an annual amount of 15 000 m^3 of fibre fraction will be handled per year.

Table F.17
Material consumption data related to the infrastructures needed for the storage of the fibre fraction.

Materials	Amount of material	Estimated life time	Amount of fibre fraction per year [m^3 per year]	Amount of fibre fraction in a life time [a] [m^3 in a life time]	Weight [per 1000 kg fibre fraction]
Storage facility					
Reinforcing steel	6 780 kg	40 years	15000 m^3 / y	600000 m^3 ($3.6*10^8$ kg)	18.8 g
Concrete	110 m^3	40 years	15000 m^3 / y	600000 m^3 ($3.6*10^8$ kg)	0.000306 m^3

a)The density of the fibre fraction was assumed to be 600 kg/m^3, based on Brauer (2006).

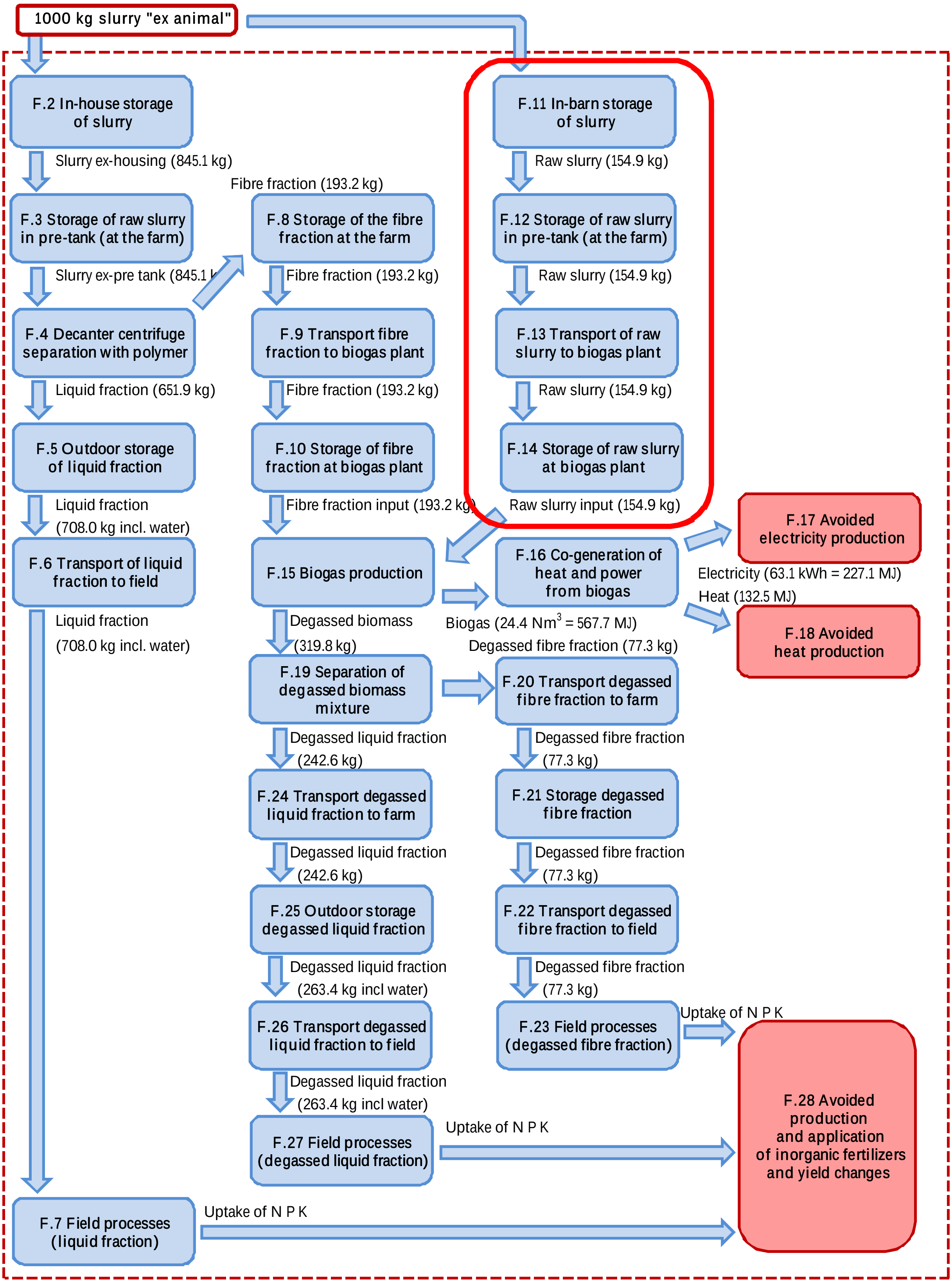
F.9 Transport of fibre fraction to biogas plant

The calculations for the transport of the fibre fraction to the biogas plant will be made for a transportation distance of 10.6 km (based on Laursen, 2009). The fibre fraction is transported by trucks. The transport is modelled by use of the Ecoinvent process “Transport, lorry >32t, EURO3” (Spielmann et al., 2007; table 5-124, p.96). As transport distance is not anticipated to have a considerable influence on the environmental impacts in the overall scenario (based on the results obtained by Wesnæs et al., 2009), no sensitivity analysis was carried out for a greater transport distance.

F.10 Storage of the fibre fraction at the biogas plant

Once at the biogas plant, the fibre fraction is stored for a very short period – from a few days to maximum a week (Rosager, 2009). As for process F.8, this means that the emissions occurring during the temporal storage of the fibre fraction at the biogas plant are considered as negligible. The equipment and materials for this storage are included in the material list for the biogas plant in table F.23.

Processes F.11 to F.14: Handling the raw slurry input for biogas: from in-house storage to storage at the biogas plant.



F.11 In-house storage of raw slurry

The assumptions and Life Cycle Inventory data for the storage of slurry in the housing units are the same as for the reference scenario (section A.2, Annex A), and thereby the same as described in section F.2.

F.12 Storage of raw slurry in pre-tank

This process is identical to the process described in section F.3. Therefore, the same life cycle data applies here.

F.13 Transport of raw slurry to biogas plant

For the transport of untreated slurry to the biogas plant, a distance of 5 km is assumed between the farm and the biogas plant. This distance is based on the fact that farmers transporting raw slurry are located nearby the biogas plant, so it pays-off to transport raw slurry rather than separated slurry.

As transport distance is not anticipated to have a considerable influence on the environmental impacts in the overall scenario (based on the results obtained by Wesnæs et al., 2009), no sensitivity analysis was carried out for a greater transport distance.

The slurry is transported by trucks. The transport is modelled by use of the Ecoinvent process “Transport, lorry >32t, EURO3” (Spielmann et al., 2007; table 5-124, p.96).

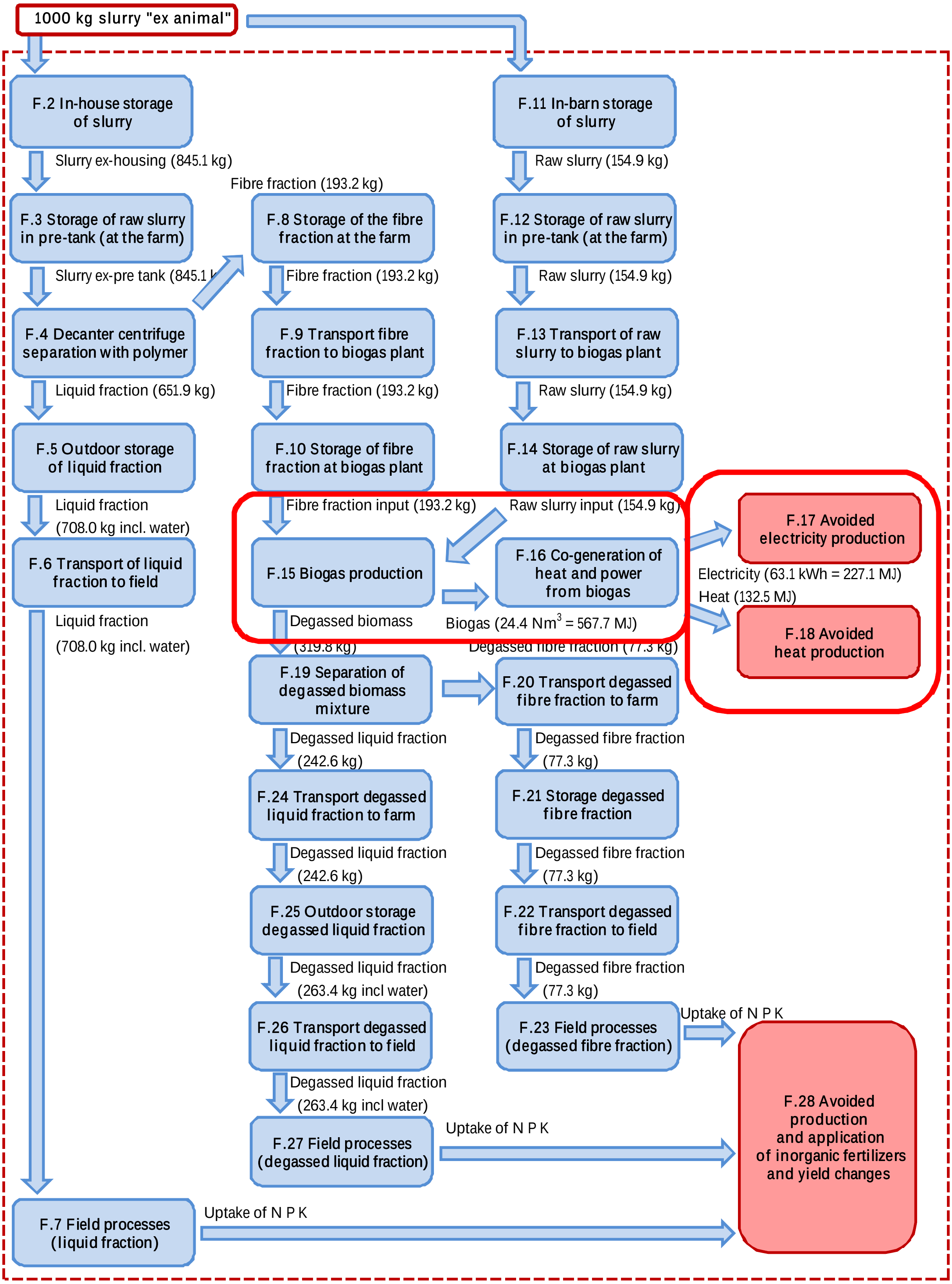
F.14 Storage of the raw slurry at the biogas plant

The raw slurry is stored at the biogas plant for a rather short time, since the storage capacity available at the biogas plant is limited. Therefore, no emissions were considered for this temporal stage. The composition of the raw slurry is therefore the same as the ex pre-tank slurry and is presented in table F.18 below.

Table F.18.
Raw slurry composition at the biogas plant, just before entering the digester (slurry from fattening pigs)

	Raw slurry at the biogas plant (ex pre-tank)
Total mass	1000 kg slurry ex pre-tank
Dry matter (DM)	69.7 kg
Ash content	13.2 kg
Volatile solids (VS) Of total VS: - easily degradable - heavy degradable	56.5 kg 34.0 kg 22.5 kg
Total-N (DJF, 2008)	*No data* *(calculated: 5.54 kg)*
Total-N in this study	5.48 kg
$NH4^+$-N	No data
Total-P	1.13 kg
Potassium (K)	2.85 kg
Carbon (C)	33.3 kg
Copper (Cu)	30.0 g
Zinc (Zn)	89.4 g
Density	1053 kg per m^3
pH	7.8

Processes F.15 to F.18: Biogas production, co-generation of heat and power and avoided heat and electricity production



F.15. Biogas production

F.15.1 Biogas principles

Biogas production occurs in anaerobic environments where organic matter is degraded by biological activity. The result of the anaerobic digestion is the release of gasses and nutrients. The produced gas is rich in methane (50-70 %) and carbon dioxide (50-30%) and with smaller amounts of other gasses such as hydrogen sulphide and nitrogen (N_2). The relative composition of the biogas mixture depends of the process conditions and the substrate digested (Nielsen, 2009), but is however mostly constituted of CH_4 and CO_2. Biogas is considered as a valuable energy source because of CH_4, since it is because of this gas that biogas is combustible (Nielsen, 2009).

According to Nielsen (2009), when pig manure is anaerobically digested at 50°C, there is between 50 and 70 % of CH_4 and between 30 and 50 % of CO_2 in the biogas. In this project, it is assumed that the biogas produced is constituted of 65 % CH_4 and 35% CO_2. This is in accordance with the biogas composition reported in the recent literature. In fact, Møller et al. (2007a) measured an average of 65 % CH_4 in a digester where a total of 60 % of fibre fraction was gradually incorporated to the biomass mixture (consisting of liquid manure from fattening pigs mixed with the fibre fraction). The biogas composition found in the Ecoinvent database (Jungbluth et al., 2007, p.180) consists of 67% CH_4 and 32.05% CO_2, the remaining 0.95 % being a mixture of N_2, O_2 and H_2S.

The biogas density[7] is 1.158 kg/Nm^3. Based on a heat value for methane of 9.94 kWh/Nm^3 CH_4, the heat value of the biogas is 6.46 kWh/Nm^3 biogas[8]. The lower heat value of the biogas in the Ecoinvent database is 24.043 MJ/Nm^3 (for the biogas used in the biogas engine, Jungbluth et al., 2007, page 180) which is in the same magnitude as the heat value in this study, namely 23.26 MJ/Nm^3 (i.e. 6.46 kWh/Nm^3 biogas * 3.6 MJ/kWh).

Biogas is not the only output of the process, as digested slurry is also produced. This digested slurry is recognized to have slightly different properties as compared to undigested slurry as a result of the digestion process. In fact, during the anaerobic degradation nutrients bound to the organic matter are released and thereby made more accessible for uptake by plants.

The biogas plant considered in this project consists of bioreactors for the biogas production, of receiving facilities and storage tanks for raw and degassed (digested) biomass, respectively, and of a co-generation unit allowing to produce heat and electricity from the biogas. In the current context, the biogas plant used for the calculations is based on a two-step digestion with an annual treatment capacity of 100 000 m^3 of biomass. Both steps are continuously operated and fully mixed in overflow tanks with a hydraulic retention time defined by the ratio between the digester volume and the daily biomass input volume.

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[7] 65% CH_4 with a density of 0.717 kg/Nm^3 plus 35% CO_2 with a density of 1.977 kg/Nm^3 gives a total density of (0.65*0.717 + 0.35*1.977) kg/Nm^3 = 1.158 kg/Nm^3.

[8] The heat value is calculated as : 9.94 kWh/Nm^3 CH_4 x 65 % CH_4 = 6.46 kWh/Nm^3 biogas.

The first step typically yields 80-90 % of the final biogas yield and is a carefully controlled process in terms of temperature, retention time and loading. The second step is a post-digestion tank often without temperature control and with a relatively low loading. The biogas plant is an air-tight system and therefore principally without any uncontrolled gaseous emissions.

The rate of biogas production depends on the nature of the biomass input (e.g. VS-content, degradability and nitrogen content) and the process conditions applied. Process temperature is highly determining for maximum gas production rate. Industrial biogas systems are typically operated at either mesophilic temperatures (around 37 °C) or thermophilic temperatures (around 52 °C). The potentially higher gas production rate in a thermophilic process can be counteracted by a temperature dependent ammonia inhibition. As the biogas scenarios investigated in the present LCA comprises a biomass with high nitrogen loading, the biogas model system will be mesophilic thereby eliminating nitrogen loading as a limiting factor when biomass mixtures are calculated.

In order to determine the final output in terms of energy, the efficiency of the co-generation unit must be known for both heat and electricity. This is further detailed in section F.16.

Table F.19 summarizes the different parameters used in this project as regarding biogas production.

Table F.19
Summary of the main parameters characterizing the biogas process

Parameter	Value
Biogas Composition	
CH_4	65 %
CO_2	35 %
Biogas density	1.158 kg/Nm^3 biogas
Engine efficiency [a)]	
Heat	46 %
electricity	40 %
Heat value	6.46 kWh/Nm^3 biogas (23.26MJ/Nm^3 biogas)

[a] See section F.16.

F.15.2 Biomass mixture entering the biogas plant

The biomass mixture input in the anaerobic digester is constituted of raw slurry (the composition of which is shown in table F.18) and fibre fraction (the composition of which is shown in table F.6). According to the composition and the degradability of both fractions, the amount of both fractions in the mixture is determined in order to obtain a biomass mixture that has a DM of approximately 10% during the digestion ***in the reactor,*** in order to obtain realistic production conditions (Jensen, 2009).

According to calculations provided by Xergi (Jensen, 2009), the 1000 kg mixture of the biomass entering the biogas plant consists of:

- 445.09 kg raw slurry (ex pre-tank)
- 554.91 kg fibre fraction

The mixture composition and mass balances is shown in table F.20 below.

Table F.20.
Mass balances for the biomass entering the biogas plant, i.e. a combination of fibre fraction and raw pig slurry (slurry from **fattening pigs**).

	Composition of the raw slurry a)	Composition of fibre fraction b)	Mass balances			Composition of biomass entering the biogas plant c)
			Amount in raw slurry	Amount in fibre fraction	Sum of mass	
	[kg per 1000 kg slurry]	[kg per 1000 kg fibre fraction]	[kg]	[kg]	[kg]	[kg per 1000 kg biomass]
Total mass	1000 kg	1000 kg	445.09 kg	554.91 kg	1000 kg	1000 kg
Dry matter (DM)	69.7 kg	265.9 kg	445.09 /1000 * 69.7 kg = 31.02 kg	554.91/1000 * 265.9 kg =147.55 kg	178.57 kg	178.57 kg
Total-N	5.48 kg	10.045 kg	445.09 /1000 * 5.48 kg = 2.44 kg	554.91/1000 * 10.045 kg = 5.574 kg	8.014 kg	8.014 kg
Total-P	1.13 kg	4.449 kg	445.09 /1000 * 1.13 kg = 0.5030 kg	554.91/1000 * 4.449 kg = 2.469 kg	2.972 kg	2.972 kg
Potassium (K)	2.85 kg	1.77 kg	445.09 /1000 * 2.85 kg = 1.269 kg	554.91 /1000 * 1.77 kg = 0.982 kg	2.251 kg	2.251 kg
Carbon (C)	33.3 kg	127.05 kg	445.09 /1000 * 33.3 kg = 14.821 kg	554.91/1000 * 127.05 kg = 70.501 kg	85.322 kg	85.322 kg
Copper (Cu)	0.03 kg	0.0475 kg	445.09 /1000 * 0.03 kg = 0.0134 kg	554.91/1000 * 0.0475 kg = 0.0264 kg	0.0398 kg	0.0398 kg
Zinc (Zn)	0.0894 kg	0.1650 kg	445.09 /1000 * 0.0894 kg = 0.0398 kg	554.91/1000 * 0.1650 kg = 0.0916 kg	0.1314 kg	0.1314 kg

a) Same as in table F.18 (which is from ex-housing slurry in Annex A)
b) Same as in table F.6
c) Composition of biomass mixture of slurry and fibre fraction entering the biogas plant, i.e. the biomass input into the digester

In this project, the functional unit is "Management of 1000 kg slurry ex-animal". The biogas production therefore has to be related to the functional unit by the use of mass balances, i.e. the values expressed per 1000 kg of biomass mixture must be converted in order to be expressed per 1000 kg of slurry ex-animal. To do this, the amount of biomass mixture (445.09 kg raw slurry plus 554.91 kg fibre fraction) used per 1000 kg of slurry ex-animal must be calculated. This calculation can be done in 6 steps:

- ***Step 1: Defining the total amount of "ex-animal" slurry involved – contribution from the raw slurry input***
  The 445.09 kg raw slurry entering the biogas plant is "ex pre-tank " corresponds to the same amount of "ex-animal" slurry, since it is assumed that no water was added during the storage in the pre-tank. Therefore, the amount of raw slurry ex-animal from this input is 445.09 kg.
- ***Step 2: Defining the total amount of "ex-animal" slurry involved – contribution from the fibre fraction input***

The 554.91 kg of fibre fraction origins from 2427.64 kg slurry ex-housing as 228.58 kg of fibre fraction is produced from 1000 kg of ex pre-tank (and hereby the same as ex-housing) pig slurry that is mechanically separated (table F.6)[9]. The mass of slurry ex-housing is considered to be the same as the slurry ex-animal (see table A.4 and A.9, Annex A). This means that 2427.64 kg of slurry ex-animal were necessary to produce the 554.91 kg of fibre fraction.

- ***Step 3: Defining the total amount of "ex-animal" slurry involved – sum of the two biomasses input***
  It means that a biomass mixture of 445.09 kg raw slurry + 554.91 kg fibre fraction origins from: 445.09 kg + 2427.64 kg = 2872.73 kg pig slurry ex-animal.
- ***Step 4: Relating the 445.09 kg of raw slurry input to the functional unit (1000 kg slurry ex-animal)***
  As the functional unit in this study is 1000 kg slurry ex-animal, the amount of "raw slurry for biogas mixture" is: 445.09 kg *1000 kg / 2872.73 kg = 154.94 kg raw slurry (ex pre-tank) per 1000 kg slurry ex-animal (and 154.94 kg raw slurry ex pre-tank corresponds to approximately 154.94 kg slurry ex-animal, as there is no water addition during the in-house storage).
- ***Step 5: Relating the 554.91 kg of fibre fraction input to the functional unit (1000 kg slurry ex-animal)***
  The amount of fibre fraction needed for the biogas mixture is : 554.91 kg *1000 kg / 2872.73 kg = 193.16 kg fibre fraction per 1000 kg slurry ex-animal (and 193.16 kg fibre fraction corresponds to approximately 845.06 kg pig slurry ex-animal [10]).
- ***Step 6: Total biomass input needed per functional unit***
  The biomass needed for the process is then 154.94 kg pig slurry (ex pre-tank) + 193.16 kg fibre fraction = 348.10 kg "biomass mixture" entering the biogas plant per 1000 kg of slurry "ex-animal".

F.15.3 Energy consumption during biogas production and heat value of the biogas produced

The amount of biogas produced is calculated assuming that the amount of VS corresponds to 80 % of DM. The following specific methane yields in Nm^3 per ton VS were assumed: Pig slurry 319 Nm^3 per ton (290 Nm^3 per ton from primary digester + 10 % extra from secondary step); fibre fraction 319 Nm^3 per ton (290 Nm^3 per ton from primary digester + 10 % extra from secondary step). Pig slurry and fibre fraction methane yield are based on Møller (2007). The fibre fraction data used are those referred to as "solids flocculated with polymer" by Møller (2007). Also, it must be remembered that it was assumed that the biogas is constituted of 65 % CH_4 and 35 % CO_2 (table F.19).

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[9] 554.91 kg fibre fraction * (1000 kg slurry ex pre-tank/228.58 kg fibre fraction) * (1000 kg slurry ex-animal/1000 kg slurry ex pre-tank) = 2427.64 kg slurry ex-animal.

[10] 193.16 kg fibre fraction * (1000 kg slurry ex pre-tank/228.58 kg fibre fraction) * (1000 kg slurry ex-animal/1000 kg slurry ex pre-tank) = 845.04 kg pig slurry ex-animal.

Using these figures, it means that a total of 70.1 Nm^3 biogas [11] per 1000 kg of "biomass mixture" is produced. The biogas density being 1.158 kg/Nm^3, a mass of 81.2 kg of biogas per 1000 kg of "biomass mixture" is therefore produced. The heat value of the biogas corresponds to 1630 MJ per 1000 kg biomass mixture"[12].

During the process, both heat and electricity are consumed. The electricity consumed for the production of biogas corresponds to the electricity used for the process plant (pumping, stirring etc.). This electricity consumption depends on the amount of biomass handled. The electricity consumed for producing the biogas is estimated as 5% of the net energy production (Jensen, 2009). This estimate is based on measurements. The electricity therefore consumed for producing the biogas corresponds to 9.06 kWh per 1000 kg "biomass mixture"[13]. This means a consumption of 0.129 kWh per Nm^3 biogas (9.06 kWh/1000 kg "biomass mixture" * 1000 kg "biomass mixture"/70.1 Nm^3 biogas). The magnitude of this value is in accordance with the values found in the literature. Jungbluth et al. (2007) reports a value of 0.132 kWh per Nm^3 biogas corresponding to the average electricity consumption for 14 Swiss biogas plants. Nielsen (2002) estimates that the internal electricity used corresponds to 0.09 kWh of electricity per m^3 of biogas produced. The value of 0.129 kWh per Nm^3 biogas used in this project therefore seems to correspond to the middle of the range of reported values. In some cases, however, the electricity consumption corresponds to 10% of the electricity produced (Jensen, 2009). Yet, this is not anticipated to be a major influence to the environmental impacts of the overall scenarios, so no sensitivity analysis was carried out for this. Instead, it is taken as a discussion point in the interpretation of the results.

The heat consumption for the process is calculated based on heating the fibre fraction and raw slurry from 8°C to the process temperature of 37°C (a temperature difference of 29°C), corresponding to 115.59 MJ per 1000 kg "biomass mixture" [14].The plant is insulated in order to reduce heat loss. Yet,

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[11] From pig slurry: 445.09 kg slurry* 69.7 kg DM/ 1000 kg slurry * 0.8 kg VS per kg DM * 319 Nm^3 CH_4 per ton VS / 0.65 Nm^3 CH_4 per Nm^3 biogas * ton/1000 kg = 12.2 Nm^3 biogas.
From fibre fraction: 554.91 kg fibre fraction * 265.9 kg DM/1000 kg fibre fraction * 0.8 kg VS per kg DM * 319.00 Nm^3 CH_4 per ton VS / 0.65 Nm^3 CH_4 per Nm^3 biogas * ton/1000 kg = 57.9 Nm^3 biogas.
Total biogas produced per 1000 kg of "biomass mixture": 70.1 Nm^3 biogas (12.2 Nm^3 from slurry + 57.9 Nm^3 from fibre fraction).

[12] This is calculated using the heat value and the total biogas produced: 6.46 kWh/Nm^3 biogas (see table F.19) * 70.1Nm^3 biogas/1000 kg "biomass mixture" * 3.6 MJ/kWh = 1630 MJ/1000 kg "biomass mixture".

[13] Estimated internal consumption of electricity in kWh per 1000 kg biomass mixture : 70.1 Nm^3 biogas/1000 kg biomass mixture x 6.46 kWh/Nm^3 biogas x 40 % engine power efficiency x 5 % internal consumption = 9.06 kWh per 1000 kg biomass mixture.

[14] It is assumed that the average temperature for the biomass is 8 °C when entering the process and that it is heated to 37°C (the process temperature). Specific heat is calculated based on the content of DM and water (calculated as 1-DM), assuming that the specific heat for DM corresponds to 3.00 kJ/kg°C and to 4.20 kJ/kg°C for water. As the DM for biomass mixture is 178.57 kg/1000 kg biomass mixture (table

some plants are equipped with heat exchangers in order to reduce the temperature difference to 15-20 °C (Rosager, 2009). The influence of this in the overall system is anticipated to be rather small and is raised as a discussion point in the interpretation of the results.

In summary, the energy consumption during the production of biogas consists of:

- 9.06 kWh of electricity per 1000 kg "biomass mixture"
- 115.59 MJ of heat per 1000 kg "biomass mixture".

F.15.4 Emissions of CH_4 and CO_2

As the biogas plant is constructed tight in order to reduce losses of biogas, the emissions to air during the digestion are assumed to be rather small.

Jungbluth et al. (2007, page 206) made a review of several references of methane emissions from agricultural biogas plants and found a range of the methane emissions of 1-4% of the produced methane for biogas plants with covered stocks. These authors however used a methane emission of 1% of the produced methane. Similarly, Börjesson and Berglund (2007) assumed that the uncontrolled losses of methane from the production of biogas correspond to 1 % of the biogas produced when the biogas is used for heat or combined heat and power. Börjesson and Berglund (2006) mention that due to the difficulties in measuring and quantifying net losses of methane from biogas production, such data are uncertain and limited. They also reports that these losses were typically assumed to 2 to 3 % in previous life cycle assessments. Sommer et al. (2001) estimated that 3% of the produced methane is lost to the environment due to leakages and non-combusted methane in the biogas engines. In this project, the estimate used by Jungbluth et al. (2007) as well as Börjesson and Berglund (2007), i.e. 1 % of the produced methane, will be used. This gives a CH_4 emission to air of 0.327 kg (see calculations in table F.21).

For the emissions of CO_2, Jungbluth et al. (2007) used an emission of 1 % of the produced carbon dioxide in the biogas. In this project, the calculated ratio between emissions of CO_2 and CH_4 in anaerobic conditions will be used, i.e. 1.42 kg CO_2 per kg CH_4 (see section F.5.5). This gives a CO_2 emission of 0.464 kg/1000 kg biomass mixture. This corresponds to 0.96 % of the CO_2 produced in the biogas[15], which is in the same magnitude as the 1% estimate of Jungbluth et al. (2007).

F.20), it involves that the water content is 1000kg – 178.57 kg = 821.43 kg/1000 kg biomass mixture. The heat consumption for heating the biomass mixture from 8°C to 37°C is thus :
For DM: 178.57 kg DM/1000 kg biomass mixture * 3.00 kJ/kg DM*°C * (37-8) °C = 15 535.59 kJ/1000 kg biomass mixture;
For water : 821.43 kg water/1000 kg biomass mixture * 4.20 kJ/kg DM*°C * (37-8) °C = 100 050.17 kJ/1000 kg biomass mixture;
Total : (15 535.59 + 100 050.17) kJ/1000 kg biomass mixture * MJ/1000 kJ = 115.59 MJ/1000 kg biomass mixture.

[15] CO_2 produced in the biogas: 70.1 Nm^3 biogas * 35% CO_2 * 1.977 kg CO_2/Nm^3 CO_2 = 48.51 kg CO_2. The CO_2 emissions of 0.464 kg estimated in this project correspond to : 0.464 kg/48.51 kg * 100% = 0.96% of the CO_2 produced in the biogas.

F.15.5 Emissions of NH_3 and N_2O

The emissions of NH_3 and N_2O from the biogas plant are assumed to be insignificant. This is based on recent publications (e.g. Marcato et al., 2008; Massé et al., 2007) where measurements showed that there are no significant losses of N during the anaerobic digestion of pig slurry. However, Loria et al. (2007), in an experiment carried in the U.S., presented an average of 10 % loss of total N during the anaerobic digestion, but it is not mentioned if this is statistically significant or not. Møller et al. (2007a), who evaluated the chemical composition of a biomass mixture consisting of pig slurry and fibre fraction from pig slurry before and after the anaerobic digestion obtained a slight increase in total N of 5.7 % after the digestion, which is due to the experimental error. This result from Møller et al. (2007a) also tends to indicate that the total N is conserved during the digestion.

F.15.6 Life cycle data and mass balances for anaerobic digestion process

In this scenario, the biogas is not upgraded (which is necessary if it is going to be used as fuel for transport). The biogas is used for co-production of electricity and heat. Table F.21 presents the life cycle data for the anaerobic digestion process.

Table F.21.
Life cycle data for the anaerobic digestion process. Data per 1000 kg biomass mixture into the biogas plant.

	Biomass mixture	Comments
Input		
Biomass mixture	1000 kg	All emissions are calculated relatively to 1000 kg “biomass mixture” (i.e. 44.5% raw slurry and 55.5% fibre fraction)
Output		
Biogas (65 % CH_4 and 35 % CO_2)	81.2 kg i.e. 70.1 Nm^3	Density 1.158 kg/Nm^3, see text.
Degassed slurry	918.8 kg	Gas output is dried. No water loss. Therefore, the only loss is the mass of the biogas : 1000 kg – 81.2 kg= 918.8 kg
Energy consumption		
Electricity	9.06 kWh	Estimated own consumption of electricity: 5 % of net production, engine efficiency of 40 % (see text). Electricity from the grid.
Heat	115.6 MJ	Heating the biomass from 8°C to 37°C, see text. Heat from the co-generation unit (see section F.16).
Emissions to air		
Carbon dioxide (CO_2)	0.464 kg	1.42 kg CO_2 per kg CH_4
Methane (CH_4)	0.327 kg	1% of the methane content of the biogas is assumed to be emitted to the environment. 70.1 Nm^3 biogas * 65% CH4 * 0.717 kg/Nm^3 * 1% = 0.327 kg CH4.
Ammonia (NH_3-N)		Assumed to be insignificant, see text
Nitrous oxide (N_2O-N)		Assumed to be insignificant, see text
Nitrogen oxides (NO_X)		Assumed to be insignificant, see text
Nitrogen monoxide(NO)		Assumed to be insignificant, see text
Nitrogen(N_2)		Assumed to be insignificant, see text
Hydrogen sulphide (H_2S)		Assumed to be insignificant compared to the emissions from the following co-production of electricity and heat.
Odour		No data
Emissions to water		
		No emissions to water
Emissions to soil		
		No emissions to soil

The composition of the degassed slurry after biogas production is shown in table F.22. It is based on mass balances from data presented in table F.21 for the total mass, the DM content and the total N.

It is acknowledged that some elements may remain in the reactor (e.g. as a precipitate). With a mixture consisting of pig slurry only, Massé et al. (2007) measured statistically significant accumulation of: 25.5 ± 7.5 % of the initial P, 41.5 ± 14.8 % of the initial Cu and 67.7 ± 22.9 % of the initial S. These represent averages obtained in two cycles. For Zn, Ca and Mn, Massé et al. (2007) measured an average retention of 18.4 ± 17.7 %, 8.7 ± 9.8 % and 21.0 ± 21.9 % respectively, but this was statistically significant only for one cycle. Similarly, in an experiment where pig slurry was digested, Marcato et al. (2008) observed significant losses for P, Ca, Mg and Mn (36 %, 44 %, 32.5 % and 32 % of the respective elements were lacking in the output slurry as compared to the input slurry). Marcato et al. (2008) explained these losses by the accumulation of these elements in the form of a precipitate in the reactor, which they confirmed by scanning electron microscopy observations. As opposed to the results of Massé et al. (2007), there were no significant losses of S, Cu and Zn in the results of Marcato et al. (2008). However, both studies agree as regarding losses of P in the bioreactor, and the magnitude are comparable. Nevertheless, it was decided, based on interviews with managers and experts of Danish biogas plants (Karsten Buchhave, 2009; Jesper Andersen, 2009 and Henrik Laursen, 2009), to consider that no losses are involved through precipitation. Given the performances of the agitator systems found in the digesters nowadays in Denmark, it is reasonable to assume that no precipitates are formed in the digesters (Norddahl, 2009). Moreover, based on the interviews mentioned above, it is considered that no acid is added in the slurry in order to prevent the formation of such a precipitate. This situation is judged representative of the recently built Danish biogas plants as well as of those to be built in the future.

Table F.22.
Mass balances for the biogas mixture before and after the biogas plant

	Composition of Mixture of slurry and fibre fraction entering the biogas plant [kg per 1000 kg biomass mixture]	Mass balance: Change during biogas production [kg]	Mass balance: Amount after biogas production [kg]	Composition of Degassed biomass after biogas production [a] [kg per 1000 kg degassed biomass]
Total mass	1000 kg	- 81.2 kg [b]	918.8 kg	1000 kg
Dry matter (DM)	178.57 kg	- 81.2 kg [c]	97.37 kg	105.98 kg
Total-N	8.014 kg	No change	8.014 kg	8.722 kg
Total-P	2.972 kg	No change	2.972 kg	3.235 kg
Potassium (K)	2.251 kg	No change	2.251 kg	2.450 kg
Carbon (C)	85.322 kg	- 38.08 kg [d]	47.24 kg	51.41 kg
Copper (Cu)	0.0398 kg	No change	0.0398 kg	0.0433 kg
Zinc (Zn)	0.0134 kg	No change	0.0134 kg	0.0146 kg

a) All the data are the same as in the precedent column, but adjusted to be expressed per 1000 kg of degassed mixture, instead of per 918.8 kg of degassed mixture.
b) This loss corresponds to the biogas produced, expressed in mass terms.
c) No water loss and therefore change in dry matter is equal to change in total mass.
d) This corresponds to the losses in the biogas itself and the losses that occurred during the digestion process:

Losses in the biogas are calculated as the sum of CH_4-C and CO_2-C: (70.1 Nm^3 biogas * 65 % CH_4 * 0.717 kg CH_4/Nm^3) * (12.011 g/mol /16.04 g/mol) + (70.1 Nm^3 biogas * 35 % CO_2 * 1.977 kg CO_2/Nm^3) * (12.011 g/mol /44.01 g/mol) = 37.707 kg C
Losses from the digestion process are the aggregated losses as CO_2-C + CH_4-C: 0.464 kg CO_2 * (12.011 g/mol /44.01 g/mol) + 0.327 kg CH_4 * (12.011 g/mol /16.04 g/mol) = 0.371 kg C
Total C loss : 37.707 kg C + 0.371 kg C = 38.08 kg C.

F.15.7 Material consumption for the anaerobic digestion plant

The materials for the anaerobic digestion plant are taken from the Ecoinvent process "Anaerobic digestion plant covered, agriculture" (Jungbluth et al., 2007, p. 197) with a capacity of 500 m^3 (biomass) and a life time of 20 years (table F.23). A typically Danish biogas plant has a treatment capacity of 100 000 m^3 biomass a year (Jensen, 2009). This includes the bioreactor only, i.e. the storage tanks and co-generation unit are not included. Electronics for operating the system are however included.

Table F.23.
Material consumption for an anaerobic digestion plant.

Materials	Weight of material in plant	Estimated life time	Amount of slurry per year [m^3 slurry per year]	Amount of slurry in a life time [m^3 slurry in a life time]	Weight [per 1000 kg slurry]
Anaerobic digestion Plant					
Concrete	120 m^3	20 years	100 000 m^3 / y	2 000 000 m^3	0.00006 m^3
Reinforcing steel	10800 kg	20 years	100 000 m^3 / y	2 000 000 m^3	5.4 g
Steel, chromium steel 18/8	1300 kg	20 years	100 000 m^3 / y	2 000 000 m^3	0.65 g
Glued laminated timber	80 m3	20 years	100 000 m^3 / y	2 000 000 m^3	0.00004 m^3
Cobber	250 kg	20 years	100 000 m^3 / y	2 000 000 m^3	0.125 g
Polystyrene, high impact	570 kg	20 years	100 000 m^3 / y	2 000 000 m^3	0.285 g
Polyethylene	170 kg	20 years	100 000 m^3 / y	2 000 000 m^3	0.085 g
Polyvinyleidenchloride	330 kg	20 years	100 000 m^3 / y	2 000 000 m^3	0.165 g
Synthetic rubber	1200 kg	20 years	100 000 m^3 / y	2 000 000 m^3	0.6 g
Electronics / PC [a)]	2 kg	5 years	100 000 m^3 / y	500 000 m^3	0.001 g

a)The computer and electronics for the operating system is not included in the Ecoinvent database. It is added in this study.

F.16 Co-generation of heat and power from biogas

The biogas produced is used for the production of electricity and heat. A biogas engine is used for this purpose. In order to estimate the net heat and electricity production, the engine efficiencies (for conversion of biogas to both heat and electricity) are needed. The efficiencies of the best available technology have been applied. According to the technical description of biogas engines from GE Energy (GE Energy, 2008), the efficiency for the electricity production is in the range of 36.7%-40.8% and the efficiency for heat production is in the range of 42.9%-48.9%, with a maximum total efficiency of 82.5-86%. Accordingly, the calculations have been carried out considering an electricity efficiency of 40% and a heat efficiency of 46%.

As detailed in section F.15.3, the system produces 70.1 Nm^3 biogas per 1000 kg of biomass mixture. As there are 348.10 kg biomass mixture per 1000 kg slurry ex-animal (see detailed calculation in section F.15.2), this corresponds to a production of 24.4 Nm^3 biogas per 1000 kg slurry ex-animal[16]. The net energy production after the co-generation unit is therefore 261.13 MJ heat plus 63.1 kWh electricity (227.1 MJ) per 1000 kg slurry ex-animal[17].

As also detailed in section F.15.3, some of the produced heat is used to fulfil the heat demand of the biogas production. The amount of heat needed for this purpose is 115.6 MJ per 1000 kg mixture input, which corresponds to 40.2 MJ per 1000 kg slurry ex-animal[18]. The heat consumption by the biogas plant thus corresponds to 40.2 MJ/ 261.13 MJ = 15 % of the heat produced. The surplus heat for the system is 261.13 MJ – 40.2 MJ = 220.9 MJ for the total system.

Yet, not all of this surplus heat can actually be used. In fact, the amount of "usable" surplus heat from the biogas plant must reflect the fact that in Denmark, according to the seasonal variations, there are periods with a surplus of heat production, which means that the heat produced at the biogas plant cannot be used during these periods, as there is no demand for it.

In the framework of the Danish LCAfood project, Nielsen (2004) assumed that only 50 % of the net heat produced by farm scale biogas plants is actually used, the remaining 50 % being simply wasted.

In the case of this project (joint scale biogas plants), it was assumed that 60 % of the surplus heat produced at the biogas plant is used, the remaining 40 % being wasted. This is a rather rough assumption based on the averaged national monthly heat demand distribution.

Therefore, out of the 220.9 MJ per 1000 kg slurry ex-animal of net surplus heat, only 132.54 MJ (i.e. 220.9 MJ * 60%) are used to fulfil the heat demand. The wasted heat thus corresponds to 88.39 MJ.

The energy produced from the biogas can be summarized as:

- 63.1 kWh electricity (227.1 MJ) per 1000 kg slurry ex-animal, all used through the national electricity grid (low voltage electricity).
- 261.13 MJ heat per 1000 kg slurry ex-animal, of which:
    - 40.2 MJ per 1000 kg slurry ex-animal is used for fulfilling the heat demand of the biogas process itself;

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[16] 348.10 kg biomass mixture (per 1000 kg slurry ex-animal) * 70.1 Nm^3 / 1000 kg biomass mixture = 24.4 Nm^3 biogas per 1000 kg slurry ex-animal.

[17] Heat produced: 24.4 Nm^3 biogas (per 1000 kg slurry ex-animal) * 23.26 MJ/ Nm^3 biogas (heat value of the biogas, see table F.18) * 0.46 (engine efficiency for heat) = 261.13 MJ heat per 1000 kg slurry ex-animal.
Electricity produced: 24.4 Nm^3 biogas (per 1000 kg slurry ex-animal) * 23.26 MJ/ Nm^3 biogas (heat value) * 0.40 (engine efficiency for electricity) = 227.1 MJ electricity per 1000 kg slurry ex-animal. This corresponds to 227.1 MJ * kWh/3.6 MJ = 63.1 kWh electricity per 1000 kg slurry ex-animal.

[18] There is 348.10 kg biomass mixture per 1000 kg slurry ex-animal, see section F.15.2. The heat required for the process is 115.6 MJ per 1000 kg mixture (section F.15.3). The heat needed per functional unit corresponds to: 348.10 kg biomass mixture / 1000 kg slurry ex-animal * 115.6 MJ / 1000 kg biomass mixture = 40.2 MJ per 1000 kg slurry ex-animal.

- 132.54 MJ per 1000 kg slurry ex-animal is used to fulfil national heat demand;
- 88.39 MJ per 1000 kg slurry ex-animal is wasted.

The emissions from the biogas engine were estimated from recent data from the Danish National Environmental Research Institute (DMU, 2009) (plants in agriculture, combustion of biogas from stationary engines).

Table F.24 presents the life cycle data related to the co-generation of heat and power from the biogas engine.

Table F.24.
Life cycle data for the co-generation of heat and power from biogas. Data per 1 MJ energy input.

	Per MJ input	Comments
Input		
Biogas	0.043 Nm^3 (1 MJ)	Amount of biogas corresponding to an energy content of 1 MJ input.[1 MJ/23.26 MJ/Nm^3] = 0.043 Nm^3.
Co-generation unit	5.0 E-9 p	Engine, generator, electric parts etc. divided by lifetime (Data from Jungbluth et al., 2007, table 13.20 of page 259)
Lubricating oil	3.0 E-5 kg	Production and disposal of used mineral oil included (Data from Jungbluth et al., 2007, table 13.20 of page 259)
Output		
Heat	0.46 MJ	The efficiency of the heat production is 46% (see table F.19)
Electricity	0.40 MJ	The electricity efficiency is 40% (see table F.19)
Emissions to air		
Carbon dioxide (CO_2)	8.36 E-2 kg	DMU (2009)
Carbon monoxide (CO)	2.73 E-4 kg	DMU (2009)
Methane (CH_4)	3.23 E-4 kg	DMU (2009)
Non-methane volatile organic compounds (NMVOC)	1.40 E-5 kg	DMU (2009)
Ammonia (NH_3-N)		No data
Nitrous oxide (N_2O)	1.59 E-7 kg	DMU (2009)
Nitrogen oxides (NO_X)	5.40 E-4 kg	DMU (2009)
Nitrogen monoxide(NO)		No data
Nitrogen(N_2)		No data
Particulates PM_{10} $PM_{2.5}$	 4.51 E-7 kg 2.06 E-7 kg	DMU (2009)
Hydrogen sulphide (H_2S)		No data
Sulphur dioxide (SO_2)	1.92 E-5 kg	DMU (2009)
Odour		No data
Emissions to water		
		No emissions to water
Emissions to soil		
		No emissions to soil

F.17 Avoided electricity production

The electricity that is replaced is the marginal electricity on the grid to which the plant is connected. As described in Annex A (section A.3.6), the modelling of marginal electricity in Denmark is based on Lund (2009), who considered detailed energy system analysis in order to determine a mix electricity marginal, considering that the marginal supplying technology differs every hour. Based on this, the Danish marginal electricity used in this project consists of 1% wind, 51% Power Plant (coal), 43% Power Plant (natural gas) and 5% electric boiler.

As 100 % coal or 100 % natural gas is generally the marginal electricity considered in life cycle assessments (Mathiesen et al., 2009), these have been used for the sensitivity analysis.

F.18 Avoided heat production

As for electricity, the heat avoided is the heat produced by the marginal heat source, i.e. the source that is actually replaced when heat is produced by the biogas engine. Yet, the marginal heat source may be variable in function of the biogas plant location. For example, if the biogas plant is connected to the district heating grid, then the heat from the biogas plant replace the marginal energy source of the combined heat and power (CHP) producing plant. This marginal energy source is then likely to be coal or natural gas. On the other hand, the biogas plant may also be connected to the natural gas grid and inject the (upgraded) biogas in the grid, as this is likely to be the case for many plants in Denmark in the future (Jensen, 2009b; Utoft, 2009), in which case the biogas would replace natural gas. Another possibility is that the biogas plant may be located in a remote location and thereby replace heat that was produced through individual boiler. There is then a range of possibilities regarding the marginal heat source for these individual boilers: wooden pellets, straw, fuel-oil. In this study, based on what is envisioned to be the future trends, it is assumed that the biogas plant is not located in a remote location, i.e. it is (or can be) connected to the district heating grid or the natural gas grid. This involves that the marginal heat source is likely to be whether coal (generating heat through CHP) or natural gas (generating heat through CHP or as used through the natural gas grid).

Coal through CHP was assumed to be the marginal heat avoided in this project (Ecoinvent process “Heat, at hard coal industrial furnace 1-10MW/RER U”, described in Dones et al. (2007), table 11.10,p.224), but a sensitivity analysis was carried out for:

- Natural gas (through CHP; Ecoinvent process: “Heat, natural gas, at boiler condensing modulating >100kW/RER U”, described in Faist-Emmernegger et al. (2007), table 13.10, p.161);

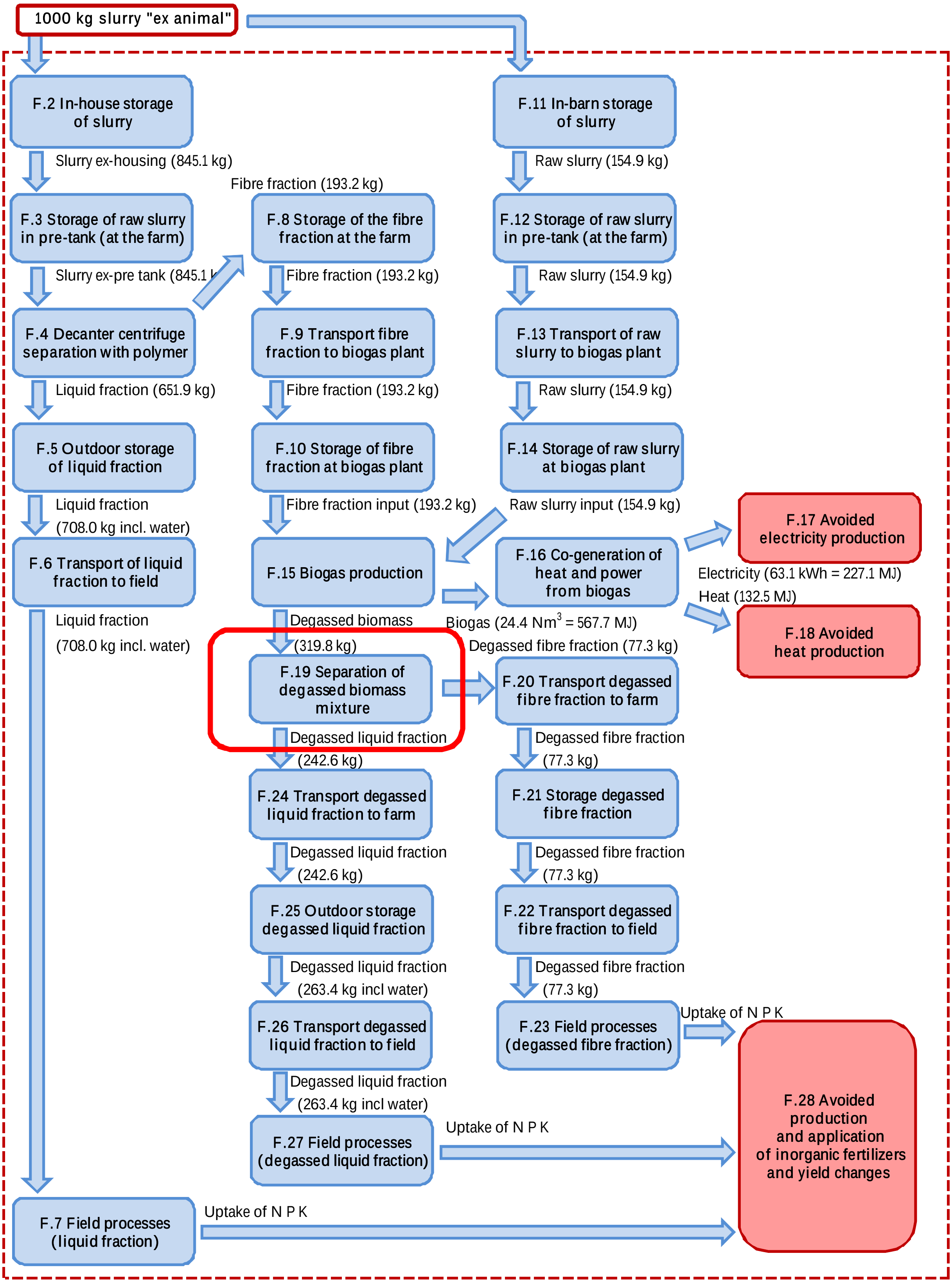
- Natural gas (through the natural gas grid; Ecoinvent process: “Natural gas, high pressure, at consumer/DK U”, described in Faist-Emmernegger et al. (2007), table 8.19, p.89-90). In this case, it is not heat that is avoided but the use (and production) of natural gas. This also means that no cogeneration takes place (no electricity or heat are produced, only biogas). This sensitivity analysis does not include the upgrading process (and neither the losses occurring during this process), so it should be considered that the actual environmental benefits are slightly lower than the results presented by this sensitivity analysis.

It can be noticed that the processes used for modelling CHP production are processes corresponding to production of heat only, for coal and for natural gas. This means that the co-production of electricity at the CHP plant is not accounted for. Though this is not correct, it was judged to be the option allowing to reflect the environmental consequences of this scenario the most accurately. This is because the Ecoinvent processes for co-generation of heat and electricity are allocated, which is incompatible with the methodology used throughout this study, i.e. consequential life cycle assessment, so it would be inconsistent to use allocated data at this stage. Un-allocating these data would however be well beyond the framework of this project, would be highly uncertain and would require external validation in order to meet the high quality standards of the Ecoinvent data. Therefore, the best compromise was judged to use the high quality data of the Ecoinvent database, but for generation of heat only, even though this project considers that CHP production is replaced and not heat only. This must be taken into account when interpreting the results.

As described in section F.16, not all the heat surpluses from the biogas plant can be used for fulfilling the national heat demand, but only 60 % of these surpluses, as there are periods where the heat demand is rather low as compared to the heat produced.

As a sensitivity analysis, the extreme situation where the surplus heat produced at the biogas plant is not used at all (i.e. no replacement) is investigated.

Process F.19: Separation of the degassed biomass mixture



F.19 Separation of digested biomass AFTER the Biogas plant

F.19.1 Separation indexes

The separation technology considered after the biogas plant is the same as in section F.4 (i.e. decanting centrifuge separation), except that no polymer is added. Therefore, the material consumption data and the electricity data are the same as in F.4.

Separation efficiencies data are based on Frandsen (2009), except for the total mass, for the same reasons as explained in section F.4.2.

As for the separation before the biogas plant, it was assumed that the DM of the solid fraction coming out of the separator would remain approximately constant independently of the water content of the degassed slurry. Based on this, the total mass of fibre fraction can be evaluated, and thereby the separation index for the total mass. Since the amount of DM in the resulting fibre fraction was measured (26.71 %, which means that there is 267.1 kg DM per 1000 kg of fibre fraction according to table 4 in Frandsen (2009)), and since the DM content of the input degassed biomass is known (105.98 kg DM per kg degassed biomass, table F.22), the mass of fibre fraction produced can be calculated. This amounts to 241.639 kg fibre fraction per 1000 kg degassed biomass[19], which means that 24.16 % of the initial mass is found in the solid fraction. The remaining mass is then going in the liquid fraction, corresponding to 75.84 % (i.e. 100 % - 24.16 %).

The separation indexes considered for the post-biogas separation are presented in table F.25. It should be noted that since no data were available for Cu and Zn, the efficiencies presented in Møller et al. (2007b) were used as the best available data.

Table F.25.
Separation indexes for separation of pig slurry AFTER the biogas plant. (polymer is not added). Data from Frandsen (2009), unless otherwise specified.

	Fibre fraction	Liquid fraction
Total mass a)	24.16%	75.84%
Dry matter (DM)	60.9%	39.1%
Total-N	21.2%	78.8%
Ammonium-N	14.6%	85.4%
Phosphorous (P)	66.2%	33.8%
Potassium (K)	9.7%	90.3%
Carbon (C) b)	60.9%	39.1%
Cooper (Cu) c)	36.2%	63.8%
Zinc (Zn) c)	42.2%	57.8%

a) This is a calculated value, see text.
b)No data. Assumed to be the same as DM.
c) From Møller et al. (2007b).

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[19] The input degassed slurry to separate contains 105.98 kg DM/1000 kg degassed biomass. Yet, 60.9% of the DM ends up in the fibre fraction with the separation indexes considered (see table F.24) i.e. 105.98 kg * 60.9% = 64.542 kg DM per 1000 kg degassed biomass. As the fibre fraction contains 267.1 kg DM per 1000 kg fibre fraction (due to measurements, see table 4 in Frandsen (2009)), the total amount of fibre fraction is: 64.542 kg DM / 1000 kg degassed biomass * 1000 kg fibre fraction/ 267.1 kg DM = 241.639 kg fibre fraction per 1000 kg degassed biomass.

F.19.2 Mass balances

The mass balances of the degassed biomass mixture before and after the separation are presented in table F.26. It should be highlighted that no data as regarding the emissions occurring during the separation process has been found, as it was also the case with the separation before the biogas is produced (i.e. process F.4). This lack of data is particularly critical as regarding ammonia emissions, which are likely to occur given the volatile nature of ammonia. Yet, it appears reasonable to assume that all the emissions likely to occur during the separation are occurring in later stages anyway, so considering them at this stage or at later stages does not change the overall results.

The life cycle data for the separation post biogas production are presented in table F.27.

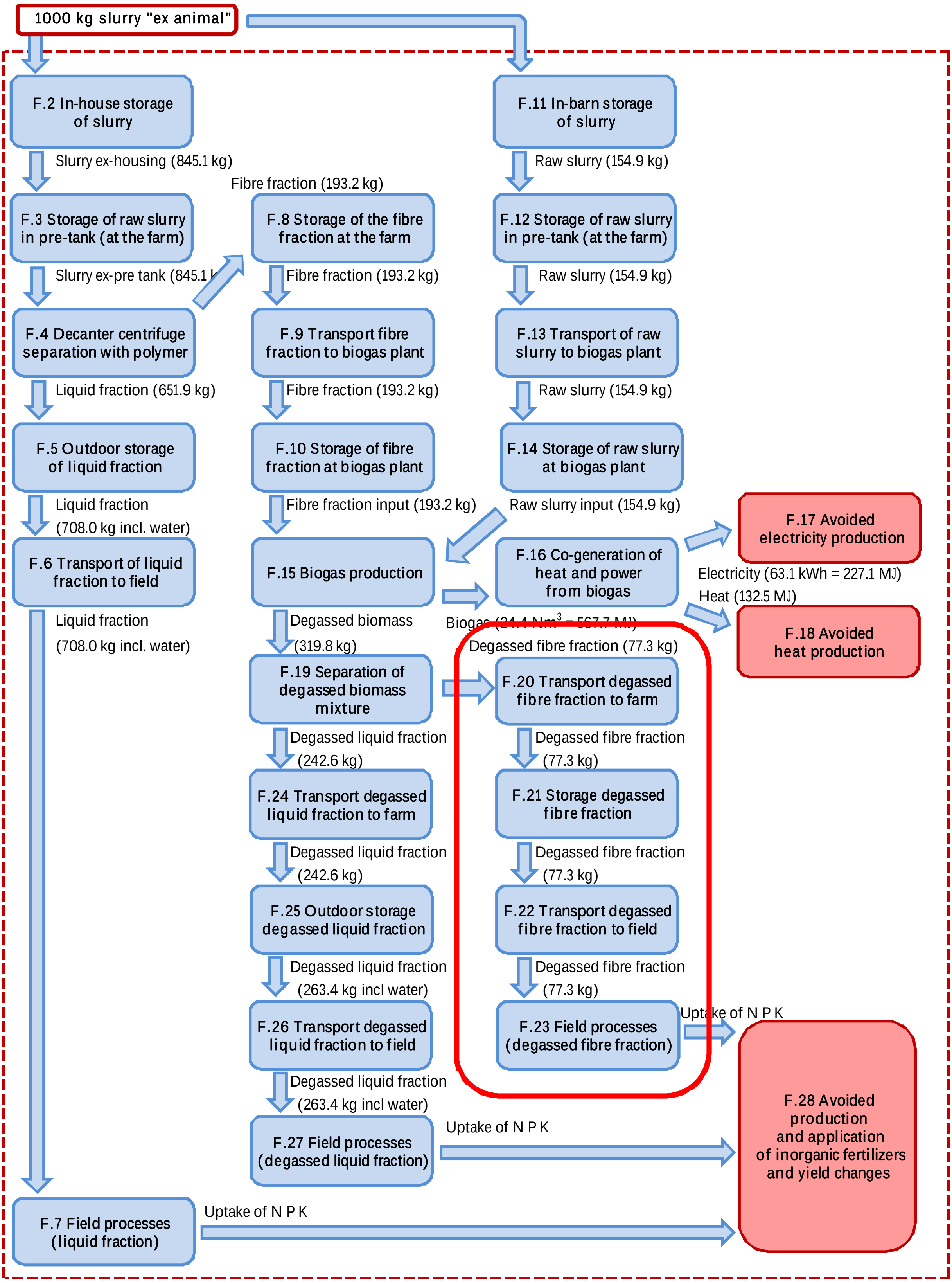
Table F.26.
Mass balances for separation of the degassed biomass.
Per 1000 kg of degassed biomass mixture “ex-digester”.

	Amount in degassed biomass mixture BEFORE separation	Separation index from table F.25	Mass Balance: Amount transferred to the fibre fraction	Mass balance: Amount transferred to the liquid fraction	Composition of the degassed fibre fraction AFTER separation Fibre fraction * 1000 / 241.6 kg	Composition of degassed liquid fraction AFTER separation Liquid fraction * 1000 kg / 758.36 kg
	[per 1000 kg ex-digester]		[per 1000 kg ex-digester]	[per 1000 kg ex-digester]	[kg per 1000 kg fibre fraction]	[kg per 1000 kg liquid fraction]
Total mass	1000 kg Slurry ex-digester	24.16%	241.6 kg	1000 kg – 241.6 kg = 758.4 kg	1000 kg Degassed fibre fraction	1000 kg degassed liquid fraction
Dry matter (DM)	105.98 kg	60.9%	105.98 kg *60.9% = 64.54 kg	105.98 kg *(100-60.9)% = 41.44 kg	267.1 kg	54.64 kg
Total-N	8.722 kg	21.2%	8.722 kg *21.2% = 1.849 kg	8.722 kg *(100-21.2)% = 6.873 kg	7.65 kg	9.06 kg
Total-P	3.235 kg	66.2%	3.235 kg *66.2% = 2.14 kg	3.235 kg *(100-66.2)% = 1.093 kg	8.86 kg	1.44 kg
Potassium (K)	2.450 kg	9.7%	2.450 kg *9.7% =0.238 kg	2.450 kg *(100-9.7)% = 2.212 kg	0.98 kg	2.92 kg
Carbon (C)	51.41 kg	60.9%	51.41 kg *60.9% = 31.31 kg	51.41 kg *(100-60.9)% = 20.10 kg	129.6 kg	26.51 kg
Copper (Cu)	0.0433 kg	36.2%	0.0433 kg *36.2% = 0.0157 kg	0.0433 kg *(100-36.2)% = 0.0276 kg	0.065 kg	0.036 kg
Zinc (Zn)	0.0146 kg	42.2%	0.0146 kg *42.2% = 0.0062 kg	0.0146 kg *(100-42.2)% = 0.0084 kg	0.025 kg	0.0111 kg

Table F.27.
Life cycle data for separation (decanter centrifuge) after the anaerobic digestion. Data per 1000 kg slurry (ex-digester).

	Fattening pig slurry	Comments
Input		
Slurry (ex-digester)	1000 kg	Degassed biomass ex-digester.
Output		
Fibre fraction	241.6 kg	
Liquid fraction	758.4 kg	
Energy consumption		
Electricity	2.184 kWh	See table F.9
Material consumption		
Separation equipment	included	See table F.10
Emissions to air		
Carbon dioxide (CO_2)		No data
Methane (CH_4)		No data
Non-methane volatile organic compounds (NMVOC)		No data
Ammonia (NH_3-N)		No data.
Nitrous oxide (N_2O-N)		No data
Nitrogen oxides (NO_X)		No data
Nitrogen monoxide(NO)		No data
Nitrogen(N_2)		No data
Particulates		No data
Hydrogen sulphide (H_2S)		No data
Sulphur dioxide (SO_2)		No data
Odour		No data
Emissions to water		
		No emissions to water

Processes F.20 to F.23: fate of the degassed fibre fraction



F.20 Transport of the degassed fibre fraction to the farm

The degassed fibre fraction will be transported to a farm where a fertilizer rich in P is needed. The transport distance from the biogas plant to this farm was modelled as 100 km. This distance takes into account the assumption that the degassed fibre fraction is not transported between the eastern and western parts of Denmark, as this would not pays off. This is in conformity with Dalgaard et al. (2006).

The fibre fraction is transported by trucks. The transport is modelled by use of the Ecoinvent process “Transport, lorry >32t, EURO3” (Spielmann et al., 2007; table 5-124, p.96).

F.21 Storage of the degassed fibre fraction

F.21.1 General description

In this study, it is assumed that the degassed fibre fraction is stored in a covered heap, outdoor. The effect of covering has tremendous impacts on the resulting emissions, as this contribute to reduce the degradation of organic matter favoured when the heap is exposed to air, and thereby the resulting gaseous emissions to the environment.

In an experiment where air-tight covered heap from solid fraction of swine manure were compared to uncovered heap, Hansen et al. (2006) observed emissions reductions of 12 %, 99 % and 88% for NH_3, N_2O and CH_4 when the heap were covered. In another study carried out by Dinuccio et al. (2008), the authors concluded from their results that, because of the emissions occurring during the (uncovered) storage phase, mechanical separation of cattle and pig slurry has the potential to increase the emissions of CO_2 equivalents by up to 30 % as compared to raw slurry. Amon et al. (2006) raise similar concerns applying particularly for the fibre fraction.

In this study, the fibre fraction is stored in heap lying on a concrete slab. The heap is covered by a polyethylene plastic sheet. This is considered as the best management practice, as this does not involve any specific energy requirements, and as this limits the C losses occurring when the heap is not covered (i.e. through the natural composting thereby occurring). This also contributes to limit the ammonia volatilization and complies with the Danish law stipulating that the stores of solid manure that do not receive daily input of materials have to be covered (Miljøministeriet, 2006).

Fibrous fractions of separated slurry that are not used for biogas production are normally stored temporally for about a week (Hansen, 2009). During that temporal storage phase, new material is regularly added until the storage capacity is full. The fibre fraction is then moved to a static store, where it is, in practice, stored for up to half a year (Hansen, 2009).

In this study, it is considered that the truck delivering the degassed fibre fraction from the biogas plant will come to the farm only once, with the amount needed by the farmer. Therefore, only static storage is involved.

F.21.2 Material consumption

Table F.28 presents the material consumption for the storage of the degassed fibre fraction. The dimensions of the storage platform used for calculating the amount of concrete needed are based on the data found in Petersen and Sørensen (2008). The annual amount of degassed fibre fraction to store is also based on Petersen and Sørensen (2008). The height of the heap is 2 m (based on Petersen and Sørensen, 2008).

Table F.28.
Material consumption for the storage of the degassed fibre fraction

Materials	Amount of material in plant	Estimated life time	Amount of degassed fibre fraction per year [kg degassed fibre fraction per year]	Amount of degassed fibre fraction in a life time [kg degassed fibre fraction in a life time]	Amount of material [per 1000 kg degassed fibre fraction]
Storage of degassed fibre fraction					
Concrete (H: 0.125 m x W: 5 m x L: 120 m)	75 m^3	40 years	520 000 kg / y	20 800 000 kg	0.003606 m^3
Polyethylene (HDPE) – 0.15 mm [a)]	190 kg	1 year	520 000 kg / y	520 000 kg	0.3654 g

a)The density considered for polyethylene is 0.96 g/cm^3.

F.21.3 Water addition

Since the heap is covered, it is considered that there is no water addition during storage. This in fact may not be exactly true since the fibre fraction might absorb some moisture from the air.

F.21.4 CH_4 emissions

Only two studies have been found in the literature where the emissions from stored degassed fibre fraction from pig slurry were assessed, and both were performed in a Danish context with a decanting centrifuge separation. The study of Hansen et al. (2006) focus specifically on the effect of covering the heap on specific gaseous emissions, while Petersen and Sørensen (2008) assessed the overall C and N losses from uncovered heaps obtained in farm-scale conditions.

Hansen et al. (2006) measured C losses corresponding to 27.9 % and 7.0 % of the initial C content (the content just before storage) for uncovered and covered heaps, respectively. This was for a 4 months storage period. Petersen and Sørensen (2008) observed total average C losses of 44 % (farm 1) and 43 % (farm 2) in the heap surfaces, for a storage duration between 5 and 9 months. These heaps were not covered.

The C losses measured by Petersen and Sørensen (2008) for uncovered heaps are much higher than those measured by Hansen et al. (2006). To explain this difference, Petersen and Sørensen (2008) highlight the fact that the ratio of aerobic to anaerobic decomposition in heaps depends on the heap size (greater in the study of Petersen and Sørensen, 2008) and on the oxygen supply (the heaps of Petersen and Sørensen, 2008, were loaded weekly while the study of Hansen et al., 2006 assessed static heaps). These differences nevertheless testify of the high degree of variability in the results induced by the different management practices as well as ambient conditions found on-site.

Hansen et al. (2006) also measured that the losses of CH_4-C corresponded to 1.3 % and 0.17 % of the initial C for uncovered and covered heaps, respectively.

In their assessment of slurry management scenarios, Sommer et al. (2009) set the CH_4 (and not C-CH_4) emissions occurring during the storage of the fibre fraction to 1.7 % of the total C, based on the study performed by Hansen et al. (2006). This, however, was for a non-degassed (and most probably uncovered) fibre fraction.

In the study of Dinuccio et al. (2008), for 30 days of open storage, the authors measured CH_4-C emissions for the fibre fraction of pig slurry corresponding to 0.68 % and 0.60 % of the VS for fibre fraction stored at 5 and 25 °C, respectively. This is for a non-degassed fibre fraction. In the present study, these figures would correspond to CH_4 emissions of 1.94 and 1.71 kg CH_4 per1000 kg fibre fraction (assuming the VS content corresponds to 80 % of the DM).

In this project, it was decided to consider the figures presented by Hansen et al. (2006) for covered storage, since these are the only data available for degassed fibre fraction stored in covered storage facilities. The data of Hansen et al. (2006) for covered storage are judged to be better data than any data for non-covered storage, since the ratio of aerobic to anaerobic decomposition are rather different for heap stored without cover. Moreover, the data of Hansen et al. (2006) were obtained with degassed fibre fraction, as in this study.

The CH_4-C emissions in this study therefore correspond to 0.17 % of the C content of the fibre fraction ex-separation. The choice of this value has been discussed with one of the leading experts in the area in Denmark, Martin Nørregaard Hansen, who validated the value as the best representative value under current data availability (Hansen, 2009). In the context of this study, it means that 0.2943 kg CH_4 per 1000 kg degassed fibre fraction is emitted.

F.21.5 CO_2 emissions

As for CH_4, data for CO_2 will mostly focus on the study of Hansen et al. (2006), for the same reasons as in the case of CH_4. In their study, Hansen et al. (2006) measured emissions of CO_2-C corresponding to 25.1 % and 1.9 % of the initial C for uncovered and covered heaps, respectively. This was for 4 months of storage.

For both covered and uncovered heap, some C losses were not accounted for in the study of Hansen et al. (2006). This corresponds to 1.5 % of the initial C for uncovered heaps, and to 4.9 % of the initial C for covered heaps.

It can be noticed that most of the C losses in the experiment of Hansen et al. (2006) occurred through CO_2 emissions, for the uncovered storage. This is also the case in the study performed by Dinuccio et al. (2008). This illustrates the importance of the aerobic degradation occurring under uncovered storage.

In this study, CO_2 losses are estimated based on the values given by Hansen et al. (2006) for covered storage, i.e. CO_2-C emissions correspond to 1.9 % of the initial C content of the degassed fibre fraction. In the present study, this amount to 9.02 kg CO_2 per 1000 kg degassed fibre fraction.

F.21.6 NH_3 emissions

The emissions of ammonia are expected to occur mostly during the first week of storage (Hansen et al., 2006; Petersen and Sørensen, 2008). Losses of N through emissions of NH_3-N measured by Hansen et al. (2006) were of 0.3 % of the initial N content, for both covered and uncovered heaps during a 4 months storage period. The authors acknowledge this is rather low. In contrast, Dinuccio et al. (2008) measured NH_3-N losses corresponding to 5.57 % and 7.12 % of the initial N content, for static fibre fraction stored at 25 °C and 5°C, respectively, during 30 days. The fibre fraction of Dinuccio et al. (2008) is not degassed and not covered, however. According to Petersen and Sørensen (2008), a “significant proportion” of the N losses during the storage of degassed fibre fraction shall be attributed to NH_3-N losses.

Based on the scarce data availability as well as on a personal communication with an active Danish expert in the area (Hansen, 2009), it was decided that the best estimation for NH_3 emissions of stored degassed fibre fraction would consist to assume that these emissions are in the same order of magnitude as those from stores of pig farmyard manure. In a recent study, Hansen et al. (2008) evaluated, from a compilation of selected emissions factors in the literature, that the NH_3-N emissions from covered stores of pig farmyard manure is 13 % of the N content in the farmyard manure before storage (table 3 in Hansen et al., 2008). This is for a storage period of more than 100 days. In the present study, this would correspond to an emission of 0.9945 kg NH_3-N per 1000 kg of fibre fraction.

Emission of NH_3 from separated fibre fraction of animal slurries is recognized as a “hot spot” from slurry management involving separation (e.g. Amon et al.,2006; Petersen and Sørensen, 2008), so the value of 13 % of the initial N content for NH_3-N emissions used in this study appears to be rather representative. The possibility of lower emissions and the influence of this to the overall system is however raised as a discussion point in the interpretation of the results.

F.21.7 N_2O emissions

Covering allow to restrict the air inflow over the heap and therefore the potential for nitrification (and thereby denitrification) processes. In fact, Hansen et al. (2006) observed emissions reduction of 99 % for covered heap as compared to uncovered heap. The emissions measured by Hansen et al. (2006) for N_2O-N correspond to 0.04 % of the initial N content for covered heap and correspond to 4.8 % of the initial N content for uncovered heap.

In this study, the value of Hansen et al. (2006) for covered storage will be used, i.e. emissions of N_2O-N corresponding to 0.04 % of the initial N content. This choice is validated by Hansen (2009).

The indirect N_2O emissions are calculated as in Annex A, i.e. based on IPCC guidelines (IPCC, 2006). Therefore, the indirect N_2O emissions are calculated as 0.01 kg N_2O-N per kg (NH_3-N + NO_x-N) volatilized.

F.21.8 NO, NO_x and N_2 emissions

As it was not possible to find data for NO, NO_2 and N_2 emissions, the same hypothesis as those detailed in section A.2.3 of Annex A were used, i.e. based on the study of Dämmgen and Hutchings (2008). In their study, they assumed that the emission of nitrogen monoxide (NO) is the same as the direct emission of nitrous oxide (N_2O) (measured as NO-N and N_2O-N). Furthermore, they assumed that emission of nitrogen (N_2) is three times as high as the direct emissions of nitrous oxide (N_2O) (measured as N_2-N and N_2O-N).

As regarding the total NO_x emissions (NO_x = NO + NO_2), it was assumed, as in Annex A, that NO_x = NO. This is because it has not been possible to find data on NO_2.

F.21.9 Life cycle data and mass balances for storage of degassed fibre fraction

Table F.29 summarizes the LCA data for the storage of degassed slurry, while table F.30 presents the mass balances. The estimation for C in the degassed fibre fraction after storage presented in table F.30 may overestimate the actual amount of C. This is because CH_4 and CO_2 emissions considered were based on the study of Hansen et al. (2006). Yet, in that study, a significant portion of the C was lost and could not be accounted for as CH_4 or CO_2 emissions. This non-accounted for portion is 4.9 % of the initial C content, for covered heap (Hansen et al., 2006), as compared to the measured 0.17 % for CH_4-C and 1.9 % for CO_2-C. In the present study, these “unexplainable losses” are not included (this would correspond to 6.25 kg C/1000 kg degassed fibre fraction in the present project).

In table F.30, it can be noticed that the change of DM is estimated as the losses of N and C. As explained in section F.5.8, it is acknowledged that this is a rough estimation, as other elements of greater molecular weight may also be lost (e.g. dissolved O_2). The estimated DM change shall therefore be seen as a minimum change, the actual DM change may in fact be greater than the one taken into account in this study.

Table F.29
Life cycle data for storage of the degassed fibre fraction. All data per 1000 kg of degassed fibre fraction.

	Fibre fraction ex-separation	Comments
Input		
Degassed fibre fraction ex-separation	1000 kg	The emissions are calculated relatively to this.
Concrete slab and polyethylene for storage	Included	See text.
Output		
Degassed fibre fraction “ex-storage”	1000 kg	No water is added. See text.
Energy consumption		
Electricity	None	See text.
Emissions to air		
Carbon dioxide (CO_2)	9.02 kg	CO_2-C = 1.9 % of C in degassed fibre fraction ex-separation (i.e. 129.6 kg), see text.
Methane (CH_4)	0.294 kg	CH_4-C = 0.17 % of C in degassed fibre fraction ex-separation (i.e. 129.6 kg), see text.
Ammonia (NH_3-N)	0.9945 kg	NH_3-N = 13 % of total N in fibre fraction ex-separation (i.e. 7.65 kg), see text.
Direct emissions of Nitrous oxide (N_2O-N)	0.00306 kg	N_2O-N = 0.04 % of total N in fibre fraction ex-separation (i.e. 7.65 kg), see text.
Indirect emissions of Nitrous oxide (N_2O-N)	0.00998 kg	0.01 kg N_2O–N per kg (NH_3–N + NO_X–N) volatilised (IPCC, 2006, table 11.3).
Nitrogen monoxide (NO-N) (representing total NO_X)	0.00306 kg	Estimate based on Dämmgen and Hutchings (2008), consisting of assuming that NO-N = (direct) N_2O-N * 1, see text.
Nitrogen dioxide (NO_2-N)	No data	No data
Nitrogen (N_2-N)	0.00918 kg	Estimate based on Dämmgen and Hutchings (2008), consisting of assuming that N_2-N = (direct) N_2O-N * 3.
Discharges to soil		
	None	Assumed to be insignificant, as the heaps are covered.

Table F.30
Mass balances for storage of degassed fibre fraction

	Degassed fibre fraction composition AFTER the separation (from table F.26) [kg per 1000 kg degassed fibre fraction]	Mass balance: Change during storage of fibre fraction [kg]	Mass balance: Amount after storage of fibre fraction [kg]	Composition of degassed fibre fraction AFTER storage [kg per 1000 kg degassed fibre fraction AFTER storage]
Total mass	1000 kg	No change	1000 kg	1000 kg
Dry matter (DM)	267.1 kg	- 3.69 kg c)	263.41 kg	263.41 kg
Total-N	7.65 kg	- 1.01 kg a)	6.64 kg	6.64 kg
Total-P	8.86 kg	No change	8.86 kg	8.86 kg
Potassium (K)	0.98 kg	No change	0.98 kg	0.98 kg
Carbon (C)	129.6 kg	- 2.68 kg b)	126.92 kg	126.92 kg
Copper (Cu)	0.065 kg	No change	0.065 kg	0.065 kg
Zinc (Zn)	0.025 kg	No change	0.025 kg	0.025 kg

[a] Changes in total N: 0.9945 kg NH_3-N + 0.00306 kg N_2O-N + 0.00306 kg NO-N + 0.00918 kg N_2-N = 1.01 kg N

[b] Changes in total C: 9.02 kg CO2 * 12.011 [g/mol] /44.01 [g/mol] + 0.294 kg CH4 * 12.011 [g/mol] /16.04 [g/mol] = 2.68 kg C

[c] The change in DM is assumed to be identical to the sum of the loss of N and C

F.22 Transport of the degassed fibre fraction to the field

The transport of the degassed fibre fraction to the field is identical to the process described in section F.6 (transport of the liquid fraction to the field).

This means that the process “Transport, tractor and trailer” from the Ecoinvent database has been used (Nemecek and Kägi, 2007, p.204), for a distance of 10 km. This includes the construction of the tractor and the trailer.

F.23 Field processes for the degassed fibre fraction

F.23.1 General description

For this process, the data from the Ecoinvent process “solid manure, loading and spreading, by hydraulic loader and spreader” (Nemecek and Kägi, 2007, p.200) has been used for the emissions occurring during spreading. This includes, among other, the diesel consumption and the consumption of spreading equipment.

F.23.2 Emissions of CH_4 and CO_2

The CH_4 emissions on the field are assumed to be negligible, as the formation of CH_4 requires an anaerobic environment, which is, under normal conditions, not the case in the top soil.

CO_2 emissions and C-binding in the soil are modelled by the dynamic soil organic matter model C-TOOL (Petersen et al., 2002; Gyldenkærne et al., 2007).

F.23.3 Emissions of NH_3

Emissions of NH_3 are estimated based on the data for solid slurry presented in a recent publication from Hansen et al. (2008). Assuming the application takes place in the spring and that the applied degassed fibre fraction is ploughed or harrowed within 6 hours after the application, the overall NH_3 losses are calculated as 40 % of the NH_4-N (based on table 18 from Hansen et al., 2008). Yet, the values presented by Hansen et al. (2008) assumed that NH_4-N corresponds to 25 % of the N content of the solid slurry ex-storage.

Applied to the data of the present study, this means that NH_3 emissions corresponds to 0.664 kg (40% * 6.64 kg N * 25 %). The NH_3-N losses therefore correspond to 0.546 kg.

F.23.4 Emissions of N_2O

The direct and indirect N_2O emissions were based on IPCC guidelines (IPCC, 2006), as in Annex A, section A.5. This considers that the direct N_2O emissions correspond to 0.01 kg N_2O-N per kg N ex-storage, while the indirect N_2O-N emissions are estimated as 0.01 kg N_2O-N per kg (NH_3-N + NO_X-N volatilized). The indirect N_2O-N emissions based on nitrate leaching are also considered, based on IPCC guidelines (IPCC, 2006), thereby they are estimated as 0.0075 kg N_2O-N per kg N leaching.

F.23.5 Emissions of NO_X and N_2-N

As in previous sections, the emissions of NO and NO_2 are combined as NO_X-emissions, as separate data on NO and NO_2 has not been available. According to Nemecek and Kägi (2007) (page 36) the NO_X emissions can be estimated as: $NO_X = 0.21 * N_2O$. When taking the molar weights into consideration this corresponds to NO_X–N = 0.1 * N_2O-N. It is considered to be a “rough expert estimate”, but since the relative contribution has minor significance for the overall results, it is considered to be adequate.

The N_2-N emissions are based on the estimates from SimDen (Vinther, 2004). For soil type JB3 the N_2-N:N_2O-N ratio is 3:1 and for soil type JB6 the N_2-N:N_2O-N ratio is 6:1.

F.23.6 Calculation of degassed fibre fraction fertilizer value

The calculation of the fertilizer value of the degassed fibre fraction is presented and detailed in section F.28.

F.23.7 Nitrate leaching

The content of C of the degassed fibre fraction is rather high, which gives rise to a substantial increase in soil C: after 10 years the C content in the soil is increased with 30.1 (JB3) and 31.8 (JB6) kg C per 1000 kg degassed fibre fraction, according to C-TOOL. The majority of the C in the degassed fibre fraction is released as CO_2 (table F.31). The above increase in soil C gives rise to a modelled increase in soil N of 10% of the C increase, corresponding to 3.01 (JB3) and 3.18 (JB6) kg N per 1000 kg degassed fibre fraction. According to this modelling, 3.63 (JB3) and 3.46 (JB6) kg N are left for the two following fates: plant uptake and all N losses (before gaseous losses).

After the gaseous losses (table F.31), there is 2.81 (JB3) and 2.44 (JB6) kg N left for harvest and leaching. For the 100 years values, there is, after the gaseous losses, 5.800 (JB3) and 5.7535 (JB6) kg N left for harvest and leaching. For simplicity, the distribution of the surplus between harvest and leaching is assumed to be as for pig slurry (table A.15), which gives the leaching values of table F.31.

When transforming the above 10-year considerations to 100-year values, the additional mineralisation of N is calculated first, utilising C-TOOL. The mineralized N is assumed to be subject to denitrification, with the same factor as for N amendment. The plant uptake value of mineralized N relative to mineral fertilizer is assumed to be an average of 65.3 % on JB3 and 73.0 % on JB6, in accordance with the calculations in Annex A, section A.5. The remainder after denitrification and harvest removal is assumed to go to N leaching, obtaining the 100-year figures in table F.31.

F.23.8 Phosphorus leaching

For P leaching, the same assumptions as those used in Annex A were used, i.e., 10% of the P applied to field has the possibility of leaching and 6% of this actually reach the aquatic recipients, based on Hauschild and Potting (2005).

F.23.9 Cu and Zn fate

As in Annex A, it is considered that the entirety of the Cu and Zn applied will leach through the water compartment.

F.23.10 Fate of the polymer

The fate of the polymer used in the separation process described in section F.4 is considered here, assuming that no losses occurred and that 100 % of the polymer is transferred to the degassed fibre fraction. This assumption is made for simplification purposes only, but is not of importance, as both fractions end up to be spread in the field. As described in section F.4, an amount of 0.90 kg of polymer was used per 1000 kg of slurry ex pre-tank input.

Kay-Shoemake et al. (1998) investigated the effect of PAM applied to agricultural soils on soil bacterial communities and nutrient cycling. They found, among others, that the bacterial numbers on soils with and without PAM application were not significantly different. They also found that PAM-treated soils planted to potatoes contained significantly higher concentrations of NO_3^- and NH_3 as compared to untreated soils. For NO_3^-, they found 36.7 mg/kg for PAM-soil as compared to 10.7 mg/kg for control soil. For NH_3, they found 1.30 mg/kg for PAM-soil as compared to 0.50 mg/kg for control soil. This suggests that some biological degradation may take place. In an extensive review on polyacrylamide (PAM) degradation (more than 150 articles were reviewed), Caulfield et al. (2002) also acknowledged this possibility (which they explained as the hydrolysis of the amide group), but they demonstrate that this degradation has to be rather limited, due to the high molecular weight of PAM that cannot pass through the biological membranes of the bacterium. This is in line with El-Mamouni et al. (2002) who suggest that PAM may simply accumulate and persist in the environment. In their review, Caulfield et al. (2002) also concluded that no evidence is existing to suggest that PAM may form free acrylamide monomer units (which are highly toxic) under biodegradation processes.

If PAM appears to be rather recalcitrant to biological degradation, it is more susceptible to undergo thermal degradation (temperatures above 200 °C), photodegradation, chemical degradation (under very acidic or very basic conditions) as well as mechanical degradation (if submitted to high shear). These degradation processes are extensively documented in Caulfield et al. (2002). In the case of application to field, photodegradation may be the most likely degradation mechanism to occur. El-Mamouni et al. (2002) actually studied the degradation of PAM submitted to UV photolysis as a pre-treatment to anaerobic and biological processes. Their results indicate that this UV irradiation pre-treatment did contribute to increase the biological degradation of PAM, under both aerobic and anaerobic conditions. However, El-Mamouni et al. (2002) highlight that the irradiation conditions used in their experiment are unlikely to occur in natural environment, as they used light intensity as low as 254 nm (the lower the wavelength, the higher the energy; visible wavelength are between 400 to 700 nm) and exposition duration ranging between 12 to 72 consecutive hours.

Based on these findings, it was considered reasonable to assume, in the framework of this study, that no degradation of the PAM occur after the application of the degassed fibre fraction to the field. As linear PAM is water-soluble (Wu and Shank, 2004; Sojka et al., 2007), it may dissolve in water during precipitation events and leak through the water compartment. Sojka et al. (2007) in fact report that very few studies have assessed the fate of PAM, as PAM cannot be easily extracted for analysis once it has been adsorbed on solid surfaces.

In this project, as the exact fate of PAM between the soil and water compartment is not known, the impact of PAM was simply considered as a discussion point as “PAM accumulation in the environment”.

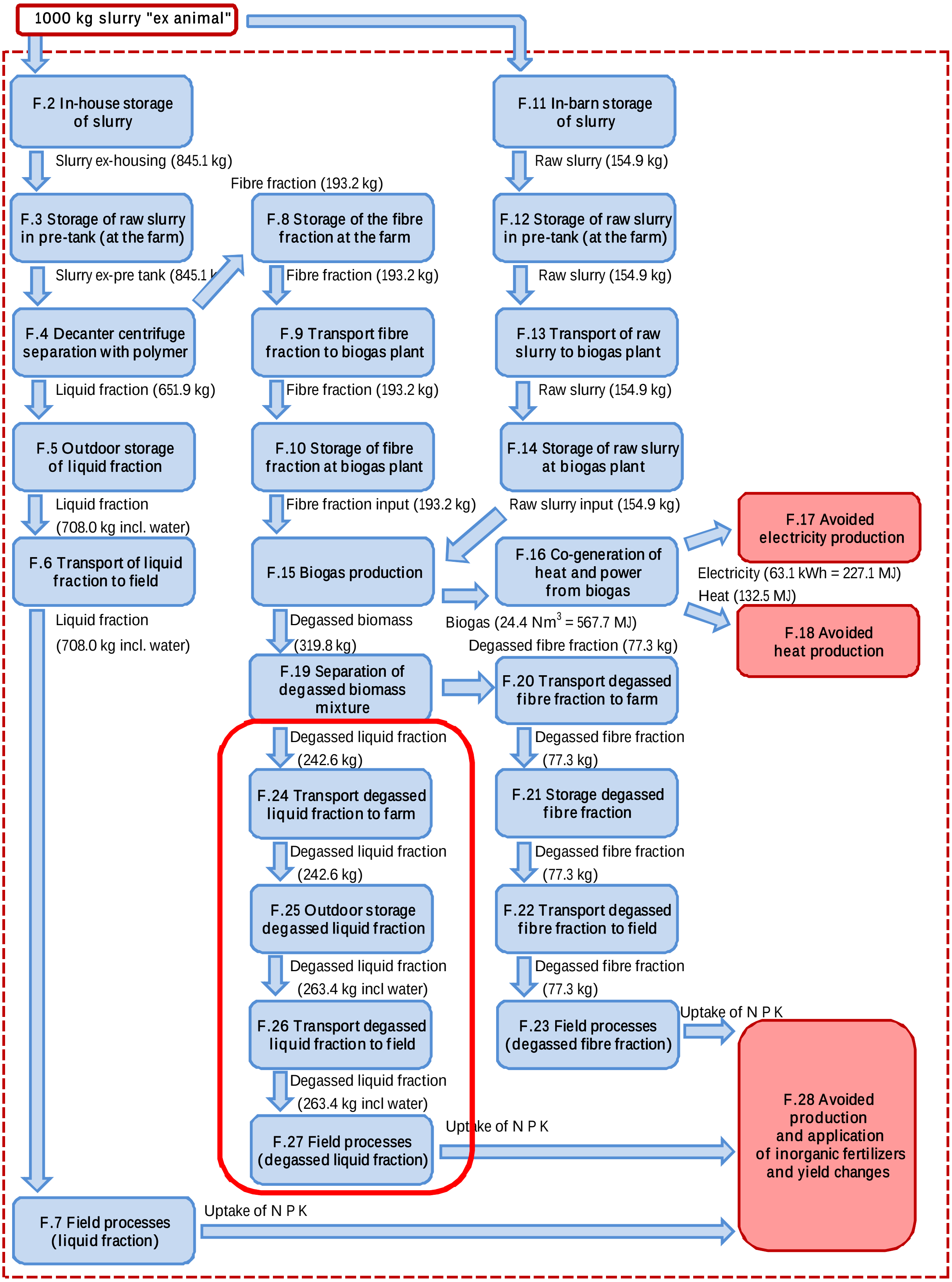
F.23.11 Life cycle data for field application of degassed fibre fraction and field processes

Table F.31 presents the life cycle data for the application of degassed ex-storage fibre fraction on the field.

Table F.31.
Life cycle data for application of degassed fibre fraction and field processes. All data per 1000 kg of “digested fibre fraction ex-outdoor storage”.

	Degassed fibre fraction after storage	Comments
Input		
Degassed fibre fraction “ex-storage”	1000 kg	
Output		
Slurry on field, fertiliser value	Fertiliser replacement value: N, P and K	See section F.28.
Energy consumption		
Diesel for spreading equipment	0.531 kg of diesel	Based on the Ecoinvent process “solid manure, loading and spreading, by hydraulic loader and spreader”.
Emissions to air		
Carbon dioxide (CO_2) Soil JB3 Soil JB6	 354.8 (434.6) kg 348.7 (432.9) kg	Modelled by C-TOOL (Gyldenkærne et al, 2007). 10 year value and 100 year in parenthesis
Methane (CH_4)	Negligible	The CH_4 emission on the field are assumed to be negligible, as the formation of CH_4 requires anoxic environment (the field is aerobic) (Sherlock et al., 2002).
Ammonia (NH_3-N) during and after application	0.546 kg	NH_3 emissions estimated as 40 % of the NH_4-N applied. The NH_4-N is assumed to be 25 % of the N content of the degassed fibre fraction ex-storage (see text). NH_3-N emissions therefore correspond to: 40% * 6.64 kg * 25 % * (14.007 g/mol N / 17.031 g/mol NH_3) = 0.546 kg NH_3-N.
Direct emissions of Nitrous oxide (N_2O-N)	0.0664 kg [0.0199 – 0.199]	0.01 [0.003 - 0.03] kg N_2O-N per kg N “ex-storage” for application of animal wastes to soil, based on IPPC (IPCC 2006; table 11.1).
Indirect emissions of Nitrous oxide (N_2O-N) Soil JB3 Soil JB6	0.0055 kg 0.011 kg (0.023 kg) 0.008 kg (0.018 kg)	Indirect emissions due to emissions of ammonia and NO_X: 0.01 kg N_2O–N per kg (NH_3–N + NO_X–N) volatilised (IPCC, 2006) Indirect emissions due to nitrate leaching: 0.0075 kg N_2O–N per kg N leaching (IPCC, 2006). 10 year values, numbers in parenthesis are 100 year values.
Nitrogen oxides (NO_x-N)	0.00664 kg	NO_X–N = 0.1 * N_2O-N according to Nemecek and Kägi (2007)
Nitrogen (N_2-N) Soil JB3 Soil JB6	 0.1992 kg 0.3984 kg	Estimated from the SimDen model ratios between N_2-N and N_2O-N (see text): 3:1 for soil JB3 and 6:1 for soil JB6.
Discharges to soil		
Nitrate leaching Soil JB3 Soil JB6	 1.53 (3.03) kg 1.08 (2.46) kg	Estimated from N partitioning (see text and table A.15, Annex A). 10 year values, numbers in parenthesis are 100 year values.
Phosphate leaching	0.886 kg P	10 % of the P applied to field (Hauschild and Potting, 2005).(Only 6 % of this reach the aquatic environment)
Copper (Cu)	0.065 kg	See table F.30
Zinc (Zn)	0.025 kg	See table F.30

Processes F.24 to F.27: fate of the degassed liquid fraction



F.24 Transport of the degassed liquid fraction to the farm

The transport of the degassed liquid fraction back to the farm is identical to the process described in section F.13 (transport of raw slurry to biogas plant).

This means that a distance of 5 km is taken into account between the farm and the biogas plant. As transport distance is not anticipated to have a considerable influence on the environmental impacts in the overall scenario (based on the results obtained by Wesnæs et al., 2009), no sensitivity analysis was carried out for a greater transport distance.

The degassed liquid is transported by trucks. The transport is modelled by use of the Ecoinvent process “Transport, lorry >32t, EURO3” (Spielmann et al., 2007; table 5-124, p.96).

F.25 Outdoor storage of the degassed liquid fraction

F.25.1 General description

The outdoor storage of the degassed liquid fraction is assumed to be stored in an outdoor concrete tank covered with a floating layer consisting of 2.5 kg of straw per 1000 kg slurry stored (as for process F.5). As in section F.5.1, the life cycle data of straw production are not included in this study, as straw is regarded as a waste product from cereal production (rather than a co-product).

F.25.2 Addition of water

The degassed liquid fraction will be diluted by precipitation in the same amount as described in F.5.2, i.e. a total of 86 kg of water.

F.25.3 Electricity consumption

As with the non degassed liquid fraction in section F.5, the electricity for pumping and stirring is taken from table A.10 (Annex A) and is adjusted by a reduction of 50 %, in order to account for the fact that the liquid fraction will offer less resistance during the pumping and stirring than does the raw slurry. This is further detailed in section F.5.

The electricity consumption thus involves : the consumption for stirring when straw is added (1.2 kWh per 1000 kg slurry), the consumption for stirring (1.2 kWh per 1000 kg slurry) and pumping (0.5 kWh per 1000 kg slurry), before application to the field. This gives an electricity consumption of 2.9 kWh per 1000 kg slurry, on which a factor of 50 % is applied, which results in an electricity consumption of 1.45 kWh per 1000 kg degassed liquid fraction.

F.25.4 Emissions of CH_4

It has not been possible to find high quality data about the CH_4 emissions occurring during the storage of degassed liquid fraction. Yet, in the latest Danish national inventory report for greenhouse gases, Nielsen et al. (2009) calculated the absolute CH_4 reduction of biogas-treated slurry by using the

IPCC methodology[20], coupled with a reduction potential of 50 % in the case of pig slurry. When applying this equation, Nielsen et al. (2009) considered the VS content of the treated slurry instead of the VS content ex-animal.

This is the methodology that will be applied in this project. The VS of the liquid fraction is estimated as 80% of the DM content. This corresponds to a VS content of 43.71 kg per 1000 kg liquid fraction.

The CH_4 emissions are therefore calculated as : 43.71 kg VS/1000 kg degassed liquid fraction * 0.45 m^3 CH_4/kg VS * 0.67 kg CH_4/m^3 CH_4 * 10% * (100-50) % = 0.659 kg CH_4/1000 kg degassed liquid fraction.

F.25.5 Emissions of CO_2

Emissions of CO_2 were estimated with the calculated ratio between emissions of CO_2 and CH_4 in anaerobic conditions, i.e. 1.42 kg CO_2 per kg CH_4 (see section F.5.5). As mentioned in section F.2, part of the produced CO_2 from the outdoor storage is emitted to air immediately and part of the CO_2 is dissolved in the slurry. However, in this life cycle assessment, it is calculated as all the CO_2 is emitted to air immediately, which makes the interpretation of the sources easier, as detailed in section F.2.

F.25.6 Emissions of NH_3

Hansen et al. (2008) state that there are no clear differences between the ammonia (NH_3) emissions from degassed slurry and untreated slurry. On one hand, the lower content of dry matter might reduce the emission of ammonia, on the other hand, TAN concentration and pH of degassed slurry are higher, which both increase the potential for ammonia emissions. Yet, Sommer (1997), who measured the NH_3 volatilization from both covered (one tank covered by straw and one tank covered by clay granules) and uncovered storage tank containing digested slurry, concluded that ammonia volatilization from the covered slurry was insignificant.

The ammonia emissions occurring during the storage of the degassed liquid fraction are therefore calculated using the same assumptions as for the reference scenario, i.e. the emission of NH_3–N are 2% of the total-N, based on Poulsen et al. (2001). The total N being 9.06 kg N/1000 kg degassed liquid fraction, the NH_3-N emissions are 0.181 kg NH_3-N per 1000 kg degassed liquid fraction.

F.25.7 Emissions of N_2O, NO-N and N_2-N

In the reference scenario, the direct N_2O emissions for storage were based on IPCC guidelines (IPCC, 2006). However, the IPCC methodology does not provide any emission factor for storage of degassed liquid fraction. The fact that the liquid fraction is degassed involves a reduction in the N_2Oemissions,

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[20] According to IPCC (2006), the methane emission can be calculated as:
CH_4 [kg] = VS [kg] * B_0 * 0.67 [kg CH_4 per m^3 CH_4] * MCF
B_0 = 0.45 m^3 CH_4 per kg VS for market swine (IPCC, 2006, Table 10A-7). The MCF value used is 10 % (for liquid slurry with natural crust cover, cool climate, in table 10-17 of IPCC (2006)). This is also the MCF recommended under Danish conditions by Nielsen et al. (2009).

as part of the most easily converted dry matter was removed during the biogas production (Mikkelsen et al., 2006).

Yet, as for the CH_4 emissions, the latest Danish national inventory report for greenhouse gases (Nielsen et al., 2009) considered a reduction potential factor for estimating the reductions in N_2O-N emissions obtained when the slurry is biogas-treated. In the case of pig slurry, this reduction potential is 40 % (Nielsen et al., 2009).

In the present project, the direct N_2O-N emissions will be estimated as in section F.5.7 (i.e. relatively to the emissions in the reference scenario but adjusted with the different N content), and this result will be multiplied by (100-40) % in order to consider the fact that the liquid fraction is degassed.

The direct N_2O-N emissions are therefore calculated as : 0.033 kg N_2O-N/1000 kg slurry ex-housing * (9.06 kg N in 1000 kg of degassed liquid fraction/ 5.48 kg N in 1000 kg slurry ex-housing) * (100-40) % = 0.0327 kg N_2O-N/1000 kg degassed liquid fraction.

The NO-N and N_2-N emissions were calculated in the same way as in Annex A, i.e. based on the study of Dämmgen and Hutchings (2008). In their study, they assumed that the emission of nitrogen monoxide (NO) is the same as the direct emission of nitrous oxide (N_2O) (measured as NO-N and N_2O-N). Furthermore, they assumed that emission of nitrogen (N_2) is three times as high as the direct emissions of nitrous oxide (N_2O) (measured as N_2-N and N_2O-N).

As regarding the total NO_x emissions ($NO_x = NO + NO_2$), it was assumed, as in Annex A, that $NO_x = NO$. This is because it has not been possible to find data on NO_2.

Therefore, this means that the NO-N emissions (and thereby the NO_x-N emissions) correspond to 0.0327 kg N_2O-N per 1000 kg degassed liquid fraction, and the N_2-N emissions correspond to 0.0981 kg per 1000 kg degassed liquid fraction.

The indirect N_2O-N emissions can be calculated as described by IPCC guidelines (IPCC, 2006), i.e. as 0.01 * (NH_3-N + NO_x-N). This gives indirect N_2O-N emissions of 0.00214 kg per 1000 kg degassed liquid fraction.

F.25.8 Life cycle data and mass balances for storage of liquid fraction

Table F.32 summarizes the LCA data for the storage of the degassed liquid fraction and presents the comparison with the storage emissions in Annex A. It must be emphasized that 1000 kg of degassed liquid fraction do ***not*** correspond to 1000 kg slurry ex-animal, so the values of Annex A versus Annex F are not directly comparable. Values from Annex A were only included since they were needed for the calculation of some of the emissions.

Table F.33 presents the mass balances of the degassed slurry in order to establish its composition after the storage. In this table, it can be noticed that the change of DM is estimated as the losses of N and C. As explained in section F.5.8, it is acknowledged that this is a rough estimation, as other elements of greater molecular weight may also be lost (e.g. dissolved O_2). The estimated DM change shall therefore be seen as a minimum change, the actual DM change may in fact be greater than the one taken into account in this study.

Table F.32
Life cycle data for storage of the degassed liquid fraction. All data per 1000 kg of degassed liquid fraction "ex-separation".

	Reference pig slurry (scenario A)	Degassed liquid fraction (fattening pig slurry) (scenario H)	Comments
Input			
Degassed liquid fraction "ex-separation"		1000 kg	The emissions are calculated relative to this.
Slurry "ex-housing"	1000 kg		
Water	86 kg	86 kg	
Concrete slurry store	Included	Included	As in scenario A.
Cut straw	2.5 kg	2.5 kg	As straw is regarded as a waste product from cereal production (rather than a co-product), the life cycle data of straw production is not included.
Output			
Slurry/degassed liquid fraction "ex-storage"	1086 kg	1086 kg	
Energy consumption			
Electricity		1.45 kWh	Electricity for pumping and stirring, see text.
Emissions to air			
Carbon dioxide (CO_2)	0.18 kg (if calculated as in Annex F :2.75 kg)	0.936 kg	Estimation based on the ratio between CH_4 and CO_2 emissions, i.e. CO_2 = 1.42 * emissions of CH_4
Methane (CH_4)	1.94 kg	0.659 kg	IPCC methodology with the VS content in the liquid fraction, and with a reduction of 50 % (see text): (54.64 kg DM *80 %) kg VS/1000 kg liquid fraction * 0.45 m^3 CH_4/kg VS * 0.67 kg CH_4/m^3 CH_4 * 10% * (100-50) % = 0.659 kg CH_4/1000 kg liquid fraction.
Ammonia (NH_3-N)	0.11 kg	0.181 kg	NH_3-N = 2% of the total-N in the degassed liquid fraction "ex-separation", see text.
Direct emissions of Nitrous oxide (N_2O-N)	0.033 kg	0.0327 kg	Estimation based on the emissions in the reference scenario, but adjusted with the relative N content. A reduction of 40 % was considered (see text): 0.033 kg N_2O-N * (9.06 kg N in degassed liquid fraction/ 5.48 kg N in slurry ex-housing) * (100-40) % = 0.0327 kg N_2O-N/1000 kg degassed liquid fraction.
Indirect emissions of Nitrous oxide (N_2O-N)	0.0014 kg	0.00214 kg	0.01 kg N_2O–N per kg (NH_3–N + NO_X–N) volatilised (IPCC, 2006, table 11.3), see text.
Nitrogen monoxide (NO-N) (representing total NO_X)	0.033 kg	0.0327 kg	Estimate based on Dämmgen and Hutchings (2008), consisting of assuming that NO-N = (direct) N_2O-N * 1, see text.
Nitrogen dioxide (NO_2-N)	No data	No data	No data
Nitrogen (N_2-N)	0.099 kg	0.0981 kg	Estimate based on Dämmgen and Hutchings (2008), consisting of assuming that N_2-N = (direct) N_2O-N * 3.
Discharges to soil and water			
	None	None	Assumed to be none, as leakages from slurry tanks are prohibited in Denmark

Table F.33.
Mass balances for storage of degassed liquid fraction

	Composition of degassed liquid fraction AFTER separation and BEFORE storage (from table F.26) [kg per 1000 kg degassed liquid fraction]	Mass balance: Change during storage of degassed liquid fraction [kg]	Mass balance: Amount after storage of degassed liquid fraction [kg]	Composition of degassed liquid fraction AFTER storage [kg per 1000 kg degassed liquid fraction AFTER storage]
Total mass	1000 kg	86 kg	1086 kg	1000 kg
Dry matter (DM)	54.64 kg	- 1.094 kg c)	53.546 kg	49.30 kg
Total-N	9.06 kg	- 0.345 kg a)	8.72 kg	8.03 kg
Total-P	1.44 kg	No change	1.44 kg	1.33 kg
Potassium (K)	2.92 kg	No change	2.92 kg	2.69 kg
Carbon (C)	26.51 kg	- 0.749 kg b)	25.76 kg	23.72 kg
Copper (Cu)	0.036 kg	No change	0.036 kg	0.034 kg
Zinc (Zn)	0.0111 kg	No change	0.0111 kg	0.0102 kg

[a] Changes in total N: 0.181 kg NH_3-N + 0.0327 kg N_2O-N + 0.0327 kg NO-N + 0.0981 kg N_2-N = 0.345 kg N

[b] Changes in total C: 0.936 kg CO2 * 12.011 [g/mol] /44.01 [g/mol] + 0.659 kg CH4 * 12.011 [g/mol] /16.04 [g/mol] = 0.749 kg C

[c] The change in DM is assumed to be identical to the sum of the loss of N and C

F.26 Transport of degassed liquid fraction to field

The transport of the degassed liquid fraction to the field is identical to the process described in section F.6 (transport of the liquid fraction to the field).

This means that the process “Transport, tractor and trailer” from the Ecoinvent database has been used (Nemecek and Kägi, 2007, p.204), for a distance of 10 km. This includes the construction of the tractor and the trailer.

F.27 Field processes for degassed liquid fraction

F.27.1 General description

As in the process described in section F.7 (field processes for [non-degassed] liquid fraction), the data from the Ecoinvent process “Slurry spreading, by vacuum tanker” (Nemecek and Kägi, 2007, p. 198) were used for the emissions related to spreading equipment “consumption”. This includes the construction of the tractor and the slurry tanker, as well as the diesel consumption. The diesel consumption due to the use of the “tanker” in the Ecoinvent process was adjusted to 0.4 litres of diesel per 1000 kg of slurry, based on Kjelddal (2009) (the same as in Annex A).

F.27.2 Emission of CH_4 and CO_2

The CH_4 emissions on the field are assumed to be negligible, as the formation of CH_4 requires an anaerobic environment, which is, under normal conditions, not the case in the top soil.

CO_2 emissions and C-binding in the soil are modelled by the dynamic soil organic matter model C-TOOL (Petersen et al., 2002; Gyldenkærne et al., 2007). The development in organic soil N is modelled by assuming a 10:1 ratio in the C to N development.

F.27.3 Emissions of NH_3

For the ammonia emissions occurring as a result of the fertilisation operations, no data were found in the literature for the specific case of the degassed liquid fraction. Yet, some data are available for degassed slurry (as compared to raw slurry) and for the (non-degassed) liquid fraction (as compared to raw slurry).

According to Hansen et al. (2008), there are no clear difference between the emissions from degassed slurry and untreated slurry since degassed slurry presents both factor promoting and inhibiting NH_3 volatilization. However, one of the main conclusion in a recent study by Möller and Stinner (2009) is that factors promoting NH_3 volatilization (higher amounts of NH_4-N and higher pH) predominate over the factors reducing the propensity for volatilization (lower viscosity, lower dry matter content). Different studies applying specifically for swine slurry also report measurements showing that digested manure is more likely to lose ammonia than untreated manure after surface application (Bernal and Kirchmann, 1992; Sommer et al., 2006). Bernal and Kirchmann (1992) measured NH_3-N losses of 14 % of the total applied N over a 9 days period from anaerobically treated pig manure mixed with soil. In Sommer et al. (2006), accumulated NH_3 volatilization after 96 h were increased of about 27.3 % on a sandy loam soil and of approximately 21.6 % on a sandy soil (for digested manure as compare to undigested manure). Börjesson and Berglund (2007) assumed an average increase of 24 % of the NH_3 emissions when digested manure is applied as compared to undigested manure (i.e. from 250 to 310 g NH_3 per tonne of manure).

As regarding the effect of the separation, a reduction of 50 % of the ammonia volatilization can be expected from a liquid fraction, as compared to raw slurry (see section F.7).

Since the liquid degassed fraction is subjected to both increasing and reducing factors as regarding the ammonia emission potential, and since no data were found specifically for this, the ammonia emissions were calculated as in the reference scenario. This is exactly as described in section F.7, but without the 50 % reduction factor in the case of the emissions occurring after application.

F.27.4 Emissions of N_2O and NO_X-N

The direct N_2O emissions are generally assumed to be smaller for degassed slurry than for untreated slurry (Sommer et al. 2001). This is because digested manure contains less easily decomposed organic matter than undigested manure (Börjesson and Berglund, 2007) and because more N is in a form already available to the plants (NH_4^+). This means that less N shall be available to microorganisms for nitrification (where NO_3^- is formed), and thus, the potential for denitrification (where NO_3^- is reduced to N_2O, and subsequently to N_2) is also reduced. This is also in accordance with Marcato et al. (2009), who concluded from their results that there are fewer risks for oxygen competition between the crops and soil bacteria (and therefore of N_2O emissions) with digested slurry as compared to undigested slurry. According to Sommer et al. (2001, table 2) N_2O emissions with degassed slurry are in the magnitude of 0.4 % of the applied N. Based on Sommer et al. (2001), Nielsen (2002) used, for field emissions with digested slurry, a reduction corresponding to 41 % of the emissions with raw slurry (i.e. from 34 to 20 g N_2O/ton manure) and Börjesson and Berglund (2007) assumed a reduction of 37.5 % (i.e. from 40 to 25 g N_2O per tonne of manure).

In this project, no specific data as regarding the direct N_2O emissions related to the use of the degassed liquid fraction were found. Therefore, the estimate of Sommer et al. (2001) for digested (but non-separated) slurry will be used as the best available data (i.e. 0.4 % of the applied N). This should be regarded as a rather rough estimate. It may also overestimate the N_2O emissions, as the slurry is both degassed and separated, which reduced significantly its content in organic N. In fact, according to Møller et al. (2007c), the centrifugal separation mainly transfers the organic N to the solid fraction, while the dissolved NH_4^+ goes in the liquid fraction.

As in section F.7, indirect N_2O emissions ***due to ammonia and NO_x*** are evaluated as 0.01 kg N_2O-N per kg of (NH_3 + NO_X) volatilized. The indirect N_2O-N emissions ***due to nitrate leaching*** correspond to 0.0075 kg N_2O-N per kg of N leaching. The emissions of NO_X-N are calculated as 0.1* direct N_2O-N, based on Nemecek and Kägi (2007).

F.27.5 Emissions of N_2-N

The N_2-N emissions are based on the estimates from SimDen (Vinther, 2004). For soil type JB3 the N_2-N:N_2O-N ratio is 3:1 and for soil type JB6 the N_2-N:N_2O-N ratio is 6:1.

F.27.6 Calculation of degassed liquid fraction fertilizer value

The fertilizer value for degassed liquid fraction is calculated and detained in section F.28.

F.27.7 Nitrate leaching

The approach from section F.7.6 is utilized, where the liquid fraction is equaled by a proportion of slurry, and an additional amount of mineral N. Taking N values after ammonia volatilization, the C:N proportion is 29.2 [kg C] / (4.80-0.02-0.48) [kg N] = 6.79 for the slurry and 23.72 [kg C] / (8.03-0.032-0.843) [kg N] = 3.32 for the liquid fraction. The "virtual" proportion of N assumed to affect the soil and plants as pig slurry is therefore 3.32/6.79 = 0.49, and the virtual proportion of N assumed to affect the soil and plants as mineral N is accordingly 0.51.

F.27.8 Phosphorus leaching

For P leaching, the same assumptions as those used in Annex A were used, i.e., 10% of the P applied to field has the possibility of leaching and 6% of this actually reach the aquatic recipients, based on Hauschild and Potting (2005).

F.27.9 Cu and Zn fate

As in Annex A, it is considered that the entirety of the Cu and Zn applied will leach through the water compartment.

F.27.10 Life cycle data for field application of degassed ex-storage liquid fraction

Table F.34 presents the life cycle data for the application of degassed ex-storage liquid fraction on the field. The results of the reference case (Annex A) are also presented for comparison purposes. However, in order to be comparable, both results must be related to the functional unit, i.e. 1000 kg slurry ex-animal.

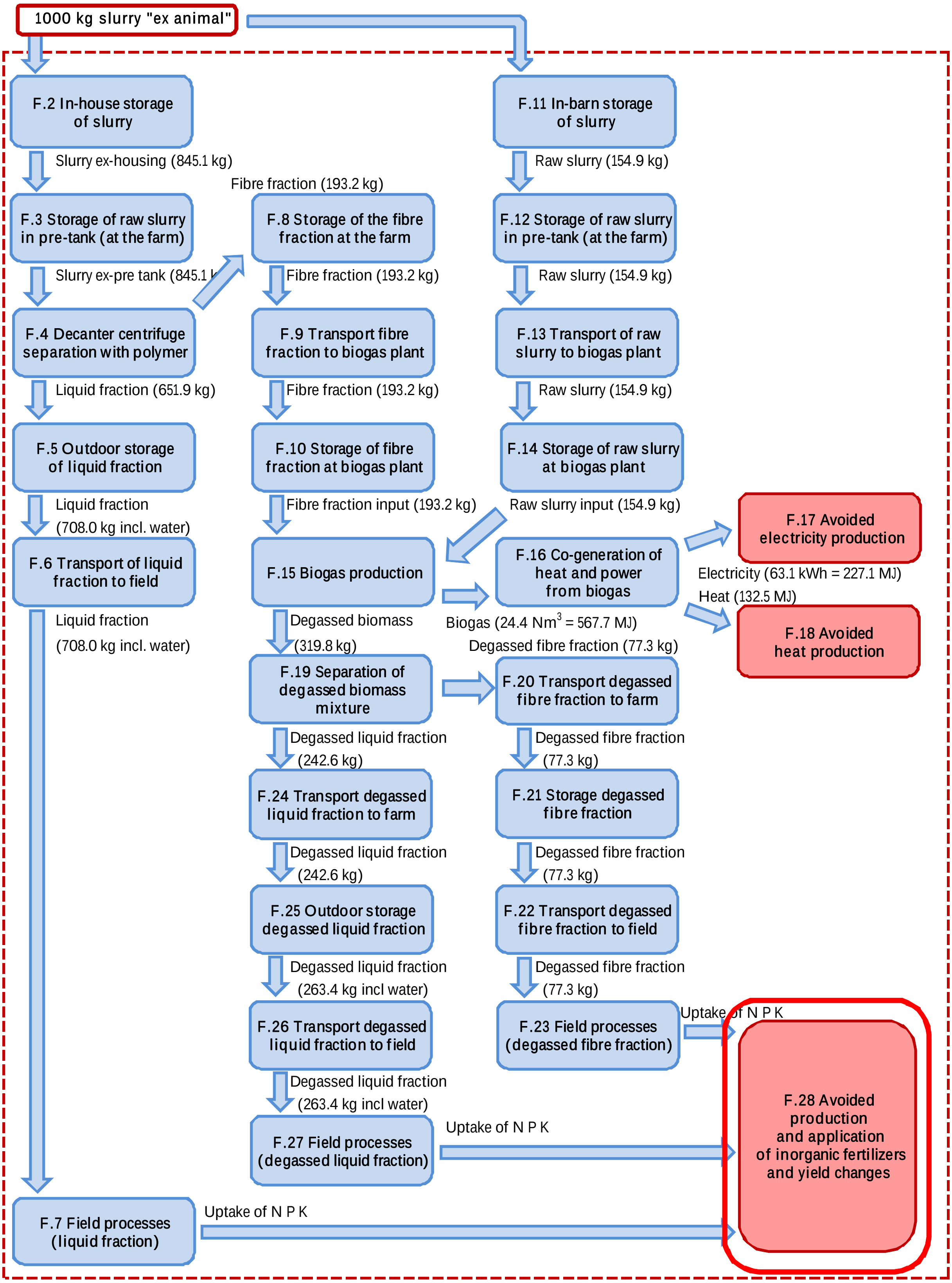
Table F.34.
Life cycle data for application of degassed liquid fraction and field processes. All data per 1000 kg of "degassed liquid fraction ex-outdoor storage".

	Fattening pig slurry	Degassed liquid fraction ex-storage	Comments
Input			
Slurry/ degassed liquid fraction "ex-storage"	1000 kg	1000 kg	Slurry / degassed liquid fraction from the outdoor storage. This is the reference amount of slurry, i.e. the emissions are calculated relative to this.
Output			
Slurry on field, fertiliser value	Fertiliser replacement value: 3.75 kg N 1.04 kg P 2.6 kg K	Fertiliser replacement value (N, P and K): See section F.28	
Energy consumption			
Diesel for slurry	0.4 litres of diesel	0.4 litres of diesel	See text.
Emissions to air			
Carbon dioxide (CO_2)			Modelled by C-TOOL (Gyldenkærne et al, 2007). 10 year value shown, 100 years value in parenthesis.
Soil JB3	81.6 kg (99.8 kg)	53.4 (77.4) kg	
Soil JB6	80.2 kg (99.4 kg)	52.3 (77.1) kg	
Methane (CH_4)	Negligible	Negligible	The CH_4 emission on the field are assumed to be negligible, as the formation of CH_4 requires anoxic environment (the field is aerobic) (Sherlock et al., 2002).
Ammonia (NH_3-N) during application	0.02 kg	0.032 kg	NH3 emissions during application: 0.5% of NH4+-N "ex-storage", the NH4+-N "ex-storage" being evaluated as 79 % of total N. 8.03 kg N * 79% * 0.5% = 0.032 kg NH_3-N
Ammonia (NH_3-N) in period after application	0.48 kg	0.843 kg	Correspond to 0.138 kg NH_3-N per kg NH_4^+-N in the degassed liquid fraction, and NH_4-N is here evaluated as 79 % of total N. This includes NH_3-N from field application. (0.138 kg NH_3-N/kg TAN-N * 79% * 8.03 kg N) – 0.032 kg NH_3-N during application = 0.843 kg NH_3-N
Direct emissions of Nitrous oxide (N_2O-N)	0.05 kg [0.015-0.15]	0.032 kg	0.4 % of the applied N, based on Sommer et al. (2001), see text.
Indirect emissions of Nitrous oxide (N_2O-N)	0.005 kg	0.00878 kg	Indirect emissions due to emissions of ammonia and NO_X: 0.01 kg N_2O–N per kg (NH_3–N + NO_X–N) volatilised (IPCC, 2006).
Soil JB3	0.014 kg (0.016 kg)	0.023 kg (0.026 kg)	Indirect emissions due to nitrate leaching: 0.0075 kg N_2O–N per kg N leaching (IPCC, 2006).
Soil JB6	0.011 kg (0.013 kg)	0.018 kg (0.020 kg)	
Nitrogen oxides (NO_x-N)	0.005 kg	0.0032 kg	NO_X–N = 0.1 * N_2O-N according to Nemecek and Kägi (2007).

Table F.34. (Continuation)
Life cycle data for application of degassed liquid fraction and field processes. All data per 1000 kg of "degassed liquid fraction ex-outdoor storage".

	Fattening pig slurry	Degassed liquid fraction ex-storage	Comments
Emissions to air			
Nitrogen (N_2-N)			Estimated from the SimDen model ratios between N_2-N and N_2O-N (see text): 3:1 for soil JB3 and 6:1 for soil JB6.
Soil JB3	0.15 kg	0.096 kg	
Soil JB6	0.30 kg	0.192 kg	
Discharges to soil			
Nitrate leaching			See text
Soil JB3	1.91 (2.12) kg N	3.09 (3.44) kg N	
Soil JB6	1.50 (1.67) kg N	2.41 (2.70) kg N	
Phosphate leaching	0.104 kg P	0.133 kg P	10% of the P applied has the possibility to leach, see text.
Copper (Cu)	0.0276 kg	0.034 kg	See table F.33.
Zinc (Zn)	0.0824 kg	0.0102 kg	See table F.33.

Process F.28: Avoided production and application of mineral fertilizers and yield changes



F.28 Avoided production and application of mineral fertilizers and yield change

F.28.1 General description

In this scenario, nitrogen is spread to the field at 3 points: Via the liquid fraction (section F.7), via the degassed fibre fraction (section F.23) and via the degassed liquid fraction (section F.27).

Before continuing this section, it is very important to clarify the difference between "The fertiliser value" and "The replaced amount of mineral fertiliser":

- ***The agronomic fertiliser value*** regards the nutritional value for the plants. It is estimated on the basis of the N amount, origin (pig, cattle) and content of organic matter in the slurry. This is used for calculating the yield increase. An increase in the crop production occurs if the agronomic fertiliser value of organic fertilisers applied in scenario F (all together for the total system) is higher than the fertiliser value for the reference scenario A, and vice versa. The calculations regarding the agronomic fertiliser value aim at representing the behaviour of the biophysical system.

- ***The replaced amount of mineral fertiliser*** is the amount of mineral fertiliser that the farmer is not allowed to bring out to the field, due to spreading the slurry (i.e. the substituted amount of mineral fertiliser). These calculations are based on Danish laws as well as on what the farmers actually do in practice. It has not a one-to-one relation to the net mineralisation in the growing season caused by the animal slurry, so it may differ from "real plant availability".

The agronomic fertiliser value and ***the replaced amount of mineral fertiliser*** are hence two different things, and in consequence they may also differ numerically.

The calculations of the replaced amount of mineral fertiliser (based on Danish law) are explained in section F.28.2. The agronomic fertiliser value and the yield changes are explained in section F.28.3.

F.28.2 Calculation of the replaced amount of mineral fertiliser

The starting point for calculating the replaced amount of mineral fertiliser is the Danish law and the guidelines for this (Gødskningsloven (2006), Gødskningsbekendtgørelsen (2008), and Plantedirektoratet (2008b)).

The foundation for the law is that there is a "quota" of nitrogen for each field, depending on the crop and soil type [21]. In addition to this, there is an upper limit for how much of the "nitrogen quota" that can be applied as animal slurry, where a maximum of 1.4 "DE per ha" is allowed for pig

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[21] Gødskningsbekendtgørelsen (2008), chapter 3, paragraph 3 and 4:
"Stk. 3. En marks kvælstofkvote opgøres på grundlag af den eller de afgrøder, der dyrkes på arealet, dog på grundlag af den senest etablerede afgrøde, hvis arealet er sået om, fordi afgrøden er slået fejl."

farmers (1.4 DE per ha corresponds to 1.4 animal unit per hectare and 1 DE equals 100 kg N – or, that is to say, did originally correspond to 100 kg N, however, this varies slightly with the Norm Data for each animal category each year).

When applying pig slurry, the N in the slurry replace 75% mineral fertiliser, which means that if applying 100 kg N in slurry, the farmer has to apply 75 kg mineral N fertiliser ***less*** (Gødskningsbekendtgørelsen (2008), paragraph 21). For example, if the farmer has a field with winter barley, and the soil type is JB3, the farmer has a "Nitrogen quota" for that field at 149 kg N per ha (Plantedirektoratet, 2008). If the farmer applies 100 kg N per ha as pig slurry, this accounts for 75 kg N per ha, which means that the farmer is allowed to apply the remaining 149 kg N per ha – 75 kg N per ha = 74 kg N per ha as mineral N fertiliser.

However, for separated slurry and for degassed slurry, the rules are not as straightforward.

For separated slurry, the "mineral fertiliser replacement values" of the separated fractions is set by the producer (i.e. the farmer or the biogas plant that separate the slurry). However, they have to follow the rule of conservation:

a) The sum of the "mineral fertiliser replacement value" of the **outgoing** fractions shall be the same as the "mineral fertiliser replacement value" of the **ingoing** slurry before separation[22].

For degassed biomass from biogas plants, there are three rules that can be applied, and the biogas plant can choose which one to apply[23]:

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[22] Gødskningsbekendtgørelsen (2008), paragraph 20:
§ 20. For det enkelte forarbejdningsanlæg gælder, at den totale mængde kvælstof i den forarbejdede husdyrgødning skal svare til den indgående totale mængde kvælstof. Ligeledes skal den andel, der skal udnyttes, af den totale mængde kvælstof i forarbejdet husdyrgødning mindst svare til andelen, der skal udnyttes, af den indgående totale mængde kvælstof […].
Stk. 2. Producenter af forarbejdet husdyrgødning fastsætter ved salg eller afgivelse til en virksomhed registreret efter lovens § 2 det totale antal kg kvælstof i gødningen og den andel af det totale antal kg kvælstof, der skal udnyttes.

[23] Gødskningsbekendtgørelsen (2008), paragraph 19: § 19. Indholdet af kvælstof i afgasset biomasse skal beregnes på grundlag af oplysninger om den mængde kvælstof i husdyrgødning, der er ***tilført*** biogasanlægget samt oplysninger om den mængde kvælstof i anden organisk gødning, der er tilført biogasanlægget, jf. § 22, stk. 6. Alternativt kan biogasanlæg, der leverer afgasset biomasse til virksomheder omfattet af lovens § 2 eller til andre virksomheder med henblik på endelig brug i virksomheder omfattet af lovens § 2, ***få indholdet af kvælstof i afgasset biomasse bestemt ved analyse*** af repræsentative prøver foretaget mindst en gang inden for perioden 1. august til 31. juli i den planperiode, gødningen skal anvendes, jf. stk. 2. Biogasanlægget skal opgøre den leverede mængde afgasset biomasse, som analysen gælder for. Stk. 2. Analyse af indhold af kvælstof i gødning skal foretages af et laboratorium, der er autoriseret hertil af Plantedirektoratet […].

Plantedirektoratet (2008b): Udnyttelsesprocenten beregner producenten (ud fra ***indgangsmaterialet*** eller analyse af repræsentative prøver). For afgasset gylle kan udnyttelsesprocenten i stedet sættes som andelen for svinegylle, der i 2007/08 er 75 pct.

b) The “mineral fertiliser replacement value” of the outgoing biomass is calculated in accordance with the ingoing biomass (“rule of conservation”).
c) The producer of the degassed biomass (i.e. the biogas plant staff) sets the “mineral fertiliser replacement value” for the degassed biomass based on representative measurement of samples of the degassed biomass.
d) Or, the “mineral fertiliser replacement value” for the degassed biomass can be set to 75% as for pig slurry.

In the following, calculations have been performed for some of the rules mentioned above.

When following rule a) + b) strictly, the “mineral fertiliser replacement value” is calculated as follows:
The replaced amount of mineral N fertiliser for Annex F is based on 4 steps:

- Step 1: Use a substitution value of 50% for the fibre fraction of slurry.
- Step 2: Acknowledging the above, make the weighted sum of the substitution values (liquid and fibre), i.e. 70 % for cattle and 75 % for pig.
- Step 3: Make a weighed sum of the substitution values for the materials entering the biogas plant – this is the substitution value for the end product before separation.
- Step 4: Use a substitution value of 50% for the fibre fraction of the degassed material from the biogas plant, and put “the rest” upon the liquid fraction (much like step 1 and 2).

The calculations for scenario F are shown in table F.35.

Table F.35.
Replaced amount of mineral N fertiliser in Annex F. All calculations per 1000 kg slurry ex-animal

Calculations
Step 1: Substitution value for fibre fraction to biogas plant Amount of fibre fraction: 193.165 kg (see figure F.1). N in fibre fraction: 10.045 kg per 1000 kg fibre fraction (see table F.6). Substitution value: 50% of 10.045 kg per 1000 kg fibre fraction * 193.165 kg fibre fraction / 1000 kg = 0.97017 kg N per 1000 kg slurry ex-animal. This is the substitution value that "belongs" to the fibre fraction that is sent to the biogas plant. This is "input" to the biogas plant.
Step 2: Acknowledging the above, make the weighted sum of the substitution values (liquid and fibre). For raw pig slurry, the substitution value is 75 %. Here rule (a) applies: "The sum of the "mineral fertiliser replacement value" of the outgoing fractions shall be the same as the "mineral fertiliser replacement value" of the ingoing slurry before separation". The mineral fertiliser replacement value of untreated, raw pig slurry is calculated based on the Danish Norm Data (DJF, 2008), which was also done in Annex A (section A.6.1). From the Danish Norm Data tables, the farmer knows the value of 5.00 kg N per kg slurry ex storage (see also table A.5 and A.1). The Danish Norm Data is what the farmer use for the accounts[1]: 5.00 kg N per 1000 kg slurry ex storage (table A. 1). However, there is only 845.064 kg slurry being separated (see figure F.1). For the system, the mineral fertiliser substitution value is then: 5.00 kg N per 1000 kg slurry ex storage * 1086 kg slurry ex storage / 1000 kg slurry ex animal * 75% = 4.0725 kg N per 1000 kg slurry ex-animal. However, there is only 845.064 kg slurry being separated (see figure F.1), i.e. 4.0725 kg/1000 kg * 845.064 kg = 3.44152 kg N. • Of this 3.44152 kg N, 0.97017 kg N belongs to the fibre fraction (as calculated in step 1). • The difference i.e.: 3.44152 kg N – 0.97017 kg N = 2.47135 kg N belongs to the liquid fraction. Mineral fertiliser replacement value for the liquid fraction (at the farm): **2.47135 kg N**
Step 3: Make a weighed sum of the substitution values for the materials entering the biogas plant. Rule (b): "Mass balance in and out of Biogas Plant – i.e. the "mineral fertiliser replacement value" of the outgoing biomass is calculated in accordance with the ingoing biomass". • The raw slurry going directly to biogas plant (without separation) has a mineral fertiliser replacement value of 4.0725 kg N per 1000 kg slurry (as described under step 2 above – 75% of 5.00 kg N ex storage). The amount of this raw slurry is 154.936 kg (see figure F.1). Its mineral fertiliser replacement value is: 4.0725 kg N per 1000 kg slurry * 154.936 kg slurry/1000 kg = 0.63098 kg N per 1000 kg slurry ex-animal. This is the substitution value for the raw slurry into the biogas plant. • At the plant, a biomass mixture is made from this raw slurry and the fibre fraction from step 1, so the substitution value for this input mixture is: 0.97017 kg N (fibre fraction, step 1) + 0.63098 kg N (raw slurry, see above) = 1.60155 kg N. This is the substitution value for the input biomass mixture going into the biogas plant, and accordingly also the substitution value for the degassed biomass mixture coming out of the biogas plant – i.e. the degassed biomass before separation. This value is used for the further calculations.
Step 4a: Use a substitution value of 50% for the fibre fraction of the degassed material from the biogas plant (like step 1) Amount of degassed fibre fraction: 77.272 kg (see figure F.1). N in degassed fibre fraction: 7.65 kg per 1000 kg fibre fraction (see table F.26). Substitution value: 50% * 7.65 kg per 1000 kg fibre fraction * 77.272 kg fibre fraction / 1000 kg = 0.2956 kg N per 1000 kg slurry ex-animal. Mineral fertiliser replacement value the degassed fibre fraction: **0.2956 kg N**
Step 4b: Calculation of the substitution value for the liquid fraction as "the rest". Here, rule (a) applies again: "The sum of the "mineral fertiliser replacement value" of the outgoing fractions shall be the same as the "mineral fertiliser replacement value" of the ingoing slurry before separation". • Total substitution value out of biogas plant = total substitution value in biogas plant, as calculated in step 3: 1.60155 kg N. • Substitution value for the liquid fraction = total from biogas plant – fibre fraction (from step 4a) = 1.60155 kg N - 0.2956 kg N = 1.30555 kg N Mineral fertiliser replacement value for the degassed liquid fraction (after the biogas plant: **1.30555 kg N**
Total amount of substituted mineral N fertiliser in the system 2.47135 kg N + 0.2956 kg N + 1.30555 kg N = **4.0725 kg N**

[1] It should be noted, that it might be more logical to use "ex housing data" for separation, but the farmers do not have information from the Norm Data on these. Furthermore, it can be argued that the loss of N during the

outdoor storage is relatively low (2% according to the Norm Data), accordingly, it does not make a big difference whether the calculations are based on "ex housing" data or "ex storage" data. Accordingly, the N substitution value of the untreated slurry (before separation) is based on the Danish Norm Data (DJF, 2008).

This 4.0725 kg N (per 1000 kg slurry ex-animal) is identical to 75% of the initial 5.00 kg N per 1000 kg slurry ex storage * 1086 kg slurry ex storage per 1000 kg slurry ex animal. This is logical, as this is the amount that is "divided" into the different fractions when applying rule (a) and rule (b) which both conserve the masses.

It should also be noted, that this amount is identical to the amount of substituted mineral N fertiliser for the reference system in Annex A.

As this study is a comparison, the calculations of the replaced amount of mineral N fertiliser are shown in table F.36, based on the explanations in Annex A, section A.6.1.

Table F.36.
Replaced amount of mineral N fertiliser in scenario A

Fraction	Calculations	Replaced amount of mineral N fertiliser [kg N per 1000 kg slurry ex animal]
Slurry	Calculations for Annex A, see explanations in section A.6.1: 75% of 5.00 kg N (per 1000 kg slurry ex storage) * 1086 kg slurry ex storage / 1000 kg slurry = 3.75 kg N * 1.086 = 4.0725 kg	4.0725 kg N

F.28.3 Yield changes

The yield changes reflect the difference in the "extra" amount of N available for "extra" crop uptake in Scenario F as compared to Scenario A. For a given scenario, this delta N can be expressed as:

ΔN = Harvested N - N received from slurry according to the substitution rule.

The N received from slurry according to the substitution rule is in fact the avoided inorganic N. Because this N is expressed in terms of inorganic N, the harvested N must be translated in terms of inorganic N as well.

For Scenario A, this delta N is referred to as ΔN_A and for Scenario F, as $\Delta N_{F.}$

The overall difference in N is then expressed as the difference between ΔN_A and ΔN_F.

This difference is afterwards translated to a response in extra wheat, as in Annex B of Wesnæs et al. (2009). This means that the production of this extra wheat does not have to be produced somewhere else in Denmark and can consequently be deduced from the system. It is acknowledged that this may be a simplistic approach to reflect the impact of a higher yield. In fact, the actual consequence of a higher yield of a given crop consists of the market response to the additional amount of that crop suddenly provided on the market. This response is however not straightforward and requires a comprehensive analysis of trade and market mechanisms (e.g. Kløverpris, 2008), which is out of the scope of the present project.

The calculation of the harvested N is made separately for each organic fertiliser type (liquid fraction, degassed fibre fraction and degassed liquid fraction):

1) Liquid fraction
    - ***Step 1: Modelling the N from liquid fraction as a given proportion of slurry N + a given amount of mineral N***
      These proportions are as described and explained in section F.7.6, i.e.: 0.21 from slurry and 0.79 from mineral N. This means that a fraction of 0.21 is assumed to affect the field as slurry and a fraction of 0.79 is assumed to affect the field as mineral N.

      After ammonia volatilisation of the liquid fraction there is 3.61-0.02-0.19= 3.4 kg N left per 1000 kg liquid fraction (table F.16).

      Giving a calculation example for JB3, this means that:

      0.21*3.4 kg N per 1000 kg liquid fraction = 0.71 kg N (per 1000 kg liquid fraction) is assumed to take the pathway of pig slurry;

      0.79*3.4 kg N per 1000 kg liquid fraction = 2.69 kg N (per 1000 kg liquid fraction) is assumed to take the pathway of mineral N;

    - ***Step 2: Amount of N harvested – portion modelled as slurry***
      Table A.15 of Annex A presents the proportion of the different fate of N following pig slurry application. Based on this table, for soil JB3, a fraction of 0.36 of the 0.71 kg N (per 1000 kg liquid fraction) is harvested after ammonia losses[24], which corresponds to:
      0.71kg N (slurry) *0.36 = 0.26 kg N harvested (per 1000 kg liquid fraction).

    - ***Step 3: Amount of N harvested – portion modelled as mineral***
      Similarly as the procedure of step 2, after ammonia losses, a fraction of 0.44 of applied mineral N is assumed to go to harvest (see table A.14, and applying the same principle as in footnote 24), which corresponds to:
      2.69 kg N (mineral N)*0.44 = 1.19 kg N harvested (per 1000 kg liquid fraction).

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[24] In table A.15, the partitioning value for ammonia volatilisation is 10.4 %. Without the ammonia losses, the sum of the values presented in table A.15 is 89.6 % (i.e. 100% - 10.4%). Based on this, the harvest partitioning value of 32.3 % (10 years) becomes: (32.3*100%)/89.6 = 36 %.

- ***Step 4: Total N harvested***
  From the 3.61 kg N applied, the harvested N is:
  0.26 kg N (step 2) + 1.19 kg N (step 3) = 1.44 kg N harvested (per 1000 kg liquid fraction).

  For JB6, the total N harvested corresponds to 1.65 kg N (per 1000 kg liquid fraction).

2) Degassed liquid fraction
   The calculation of harvested N for degassed liquid fraction follows the exact same 4 steps described for the liquid fraction.

   The proportion of N modeled as slurry and as mineral N is however based on section F.27.7 and are as follow: 0.49 from slurry and 0.51 from mineral N.

   As a result, the N harvested is 2.87 kg N on JB3 and 3.29 kg N on JB6 (per 1000 kg degassed liquid fraction).

3) Degassed fibre fraction
   For degassed fibre fraction, there is, for soils JB3 and JB6 respectively, 2.81 and 2.44 kg N left for harvest and leaching after all gaseous losses, according to the calculations of section F.23.7. Knowing the amount of N leaching for each soil types (table F.31), the N left for harvest can be calculated by a simple difference.

   This gives a harvest of 1.2752 kg N for soil JB3 (per 1000 kg degassed fibre fraction) and 1.3434 kg N for soil JB6 (per 1000 kg degassed fibre fraction).

Aggregating the amount of N harvested from each of these 3 organic fertilizer and taking into account the amount of each that is actually applied (figure F.1), the total harvested N for soil JB3 is:

[1.43 kg N per 1000 kg liquid fraction * 708 kg liquid fraction/1000 kg slurry ex-animal] + [1.2752 kg N per 1000 kg degassed fibre fraction *77.3 kg degassed fibre fraction /1000 kg slurry ex-animal] + [2.87 kg N kg degassed liquid fraction *263.4 kg degassed liquid fraction /1000 kg slurry ex-animal] = 1.873 kg N harvested on soil JB3 per 1000 kg slurry ex-animal.

On soil JB6 the amount of harvested N is 2.139 kg N per 1000 kg slurry ex-animal.

As this harvested N will be used in an equation where the N is expressed in term of mineral N, it must be translated in terms of mineral N.

To do so, the amount of mineral N needed to obtained these harvest N (1.873 kg N on soil JB3 and 2.139 kg N on soil JB6) must be determined. This can be done through the partitioning factors presented in table A.14 of Wesnæs et al. (2009). This harvested N equivalent therefore corresponds to:

> 1.873 kg N harvested/0.431(see table A.14) =4.3467 kg N harvest equivalent for soil JB3 (per 1000 kg slurry ex-animal).

2.139 kg N harvested/0.494(see table A.14) =4.3308 kg N harvest equivalent for soil JB6 (per 1000 kg slurry ex-animal).

Therefore, ΔN_F corresponds to :

Soil JB3: 4.3467 kg N – 4.0725 kg N (table F.35) = 0.2742 kg N per 1000 kg slurry ex-animal

Soil JB6: 4.3308 kg N – 4.0725 kg N (table F.35) = 0.2583 kg N per 1000 kg slurry ex-animal

For Scenario A, the calculation of harvested N is more straightforward, as it is simply the amount of N in the slurry ex-storage minus the ammonia losses, on which the partitioning ratios of table A.15 of Wesnæs et al. (2009) are applied to determine the N harvested. Then the equivalent in mineral N can be determined as above, using the values presented on table A.14 of Wesnæs et al. (2009). This gives:

Soil JB3: (4.8-0.02-0.48)*36.05% kg N per 1000 kg slurry ex-storage *(1086 kg slurry ex-storage/1000 kg slurry ex-animal) *(1/0.431) = 3.9096 kg N harvest equivalent for soil JB3 (per 1000 kg slurry ex-animal).

Soil JB6: (4.8-0.02-0.48)*41.4% kg N per 1000 kg slurry ex-storage *(1086 kg slurry ex-storage/1000 kg slurry ex-animal) *(1/0.494) = 3.9096 kg N harvest equivalent for soil JB6 (per 1000 kg slurry ex-animal).

Therefore, ΔN_A corresponds to :

Soil JB3: 3.9096 kg N – 4.0725 kg N (table F.36) = -0.1629 kg N per 1000 kg slurry ex-animal

Soil JB6: 3.9096 kg N – 4.0725 kg N (table F.36) = -0.1629 kg N per 1000 kg slurry ex-animal.

The overall N difference between both scenarios corresponds to:

$\Delta N_F - \Delta N_A$ = 0.2742 kg N – (-0.1629 kg N) = 0.4371 kg N surplus for JB3 (per 1000 kg slurry ex-animal)

$\Delta N_F - \Delta N_A$ = 0.2583 kg N – (-0.1629 kg N) = 0.4212 kg N surplus for JB6 (per 1000 kg slurry ex-animal)

According to the yield N responses (see section A.5.5, Annex A and section B.10, Annex B), one kg extra mineral N yields:

- Soil JB3: 9.0 kg more wheat grain;
- Soil JB6: 8.1 kg more wheat grain;

The yield increase is therefore:

For soil JB3: 0.4371 kg N surplus * 9.0 kg extra wheat/kg N surplus = 3.93 kg extra wheat (per 1000 kg slurry ex-animal).

For soil JB6: 0.4212 kg N surplus * 8.1 kg extra wheat/kg N surplus = 3.41 kg extra wheat (per 1000 kg slurry ex-animal).

This same procedure was also applied with the 100 year values for both soil types.

F.28.4 Avoided P and K mineral fertilisers

In this scenario, it is assumed that the degassed fibre fraction is transported to fields with lack of phosphorous. This is in fact the whole purpose of separating the degassed biomass after the biogas plant: To collect the main part of the phosphorous in order to increase the possibilities for using this as fertiliser where P is need (at fields with P deficiency) instead of at the fields close to the pig farm areas where there is surplus phosphorus in the soil (mainly in Jutland).

Accordingly, as the degassed fibre fraction (which contains the main part of the phosphorous) is transported to fields with phosphorous deficiency, it is assumed that 100 % of the phosphorous in this fraction replace mineral P fertiliser.

It is assumed that the same, i.e. 100 % replacement, applies for potassium (K). The actual amount of K substituted may in fact be less than 100 % if the K applied is greater than the crops needs. However, as previous modelling (e.g. Wesnæs et al., 2009) showed that the avoided K fertilisers have a rather insignificant effect on the overall environmental impacts of slurry management, it is believe that the amount of K avoided (100 % or less) is not likely to affect the results.

The avoided emissions per kg of inorganic N, P and K avoided are modelled as in Annex A, Table A.18.

Annex G. Biogas production with cow slurry and fibre fraction from a mechanical-chemical separation–Life Cycle Inventory data

G.1 System description

This annex contains Life Cycle Inventory data for biogas production from a mixture of fibre fraction (from mechanically separated slurry, flocculated with polymer) and raw slurry, both from dairy cows. The separation process used in this annex is considered as a “best available technology” for biogas production. The resulting fibre fraction has a degradation potential similar to the one of raw slurry. The biogas is used for co-production of heat and power. The biogas engine used for the generation of heat and power is also considered as a “best available technology”, as the engine used has conversion efficiencies ranking in the highest available range. The processes described and used for this scenario were built in collaboration with Xergi A/S, as Xergi A/S has experience and data for more than 30 biogas plants established throughout the country. The degassed slurry resulting from the anaerobic digestion is mechanically separated again, but without polymer addition. The liquid fraction is then used on field as a fertilizer, and so is the fibre fraction.

Although biogas exclusively from slurry input (i.e. without supplementary addition of easily degradable carbon) is not yet the most common practice in Denmark, it is likely to become an important alternative for the Danish panorama. This is due to the limited availability of the organic waste or the other C-source material that are actually co-digested with the slurry. Co-digesting the raw slurry is practiced in order to ensure the economic feasibility of biogas production. Moreover, the Danish government has set the objective to use more than 50 % of the slurry produced in Denmark for biogas production, in which case the possibility to make biogas from 100 % slurry input represents an interesting option. Several plants running on inputs from slurry only (i.e. raw slurry and separated fibre fraction) are currently under development throughout the country, and the first one has just been put into operation (Morsø Bioenergi was inaugurated 15 of June 2009).

The present annex describes the process flow for a biogas scenario comprising a total of 28 main processes, which were divided into 8 main sections:

- Section 1 : Processes G.2 to G.7
  This section considers the slurry from which the fibre fraction input in the biomass mixture (for biogas) origins. It starts with the raw slurry being produced in the dairy cow barn and stored in the barn (G.2). The slurry is then stored in the pre-tank (G.3) and separated (G.4). This section then continues with the fate of the liquid fraction only. The liquid fraction is stored outdoor (G.5), until it is transported to the field (G.6) and used as a fertilizer (G.7).
- Section 2 : Processes G.8 to G.10
  This section is a continuation of the previous, and starts with the fibre fraction output from the separation process (G.4). The fibre fraction is stored on-farm (G.8), transported to the biogas plant (G.9) and temporarily stored at the biogas plant (G.10).
- Section 3 : Processes G.11 to G.14
  This section focus on the raw slurry input in the biomass mixture (for biogas). It begins with the raw slurry being produced in the dairy cow barn and stored in the barn (G.11). The slurry is then stored in pre-

tank at the farm (G.12), and transported to the biogas plant (G.13). Once at the biogas plant, the raw slurry is stored temporarily (G.14).

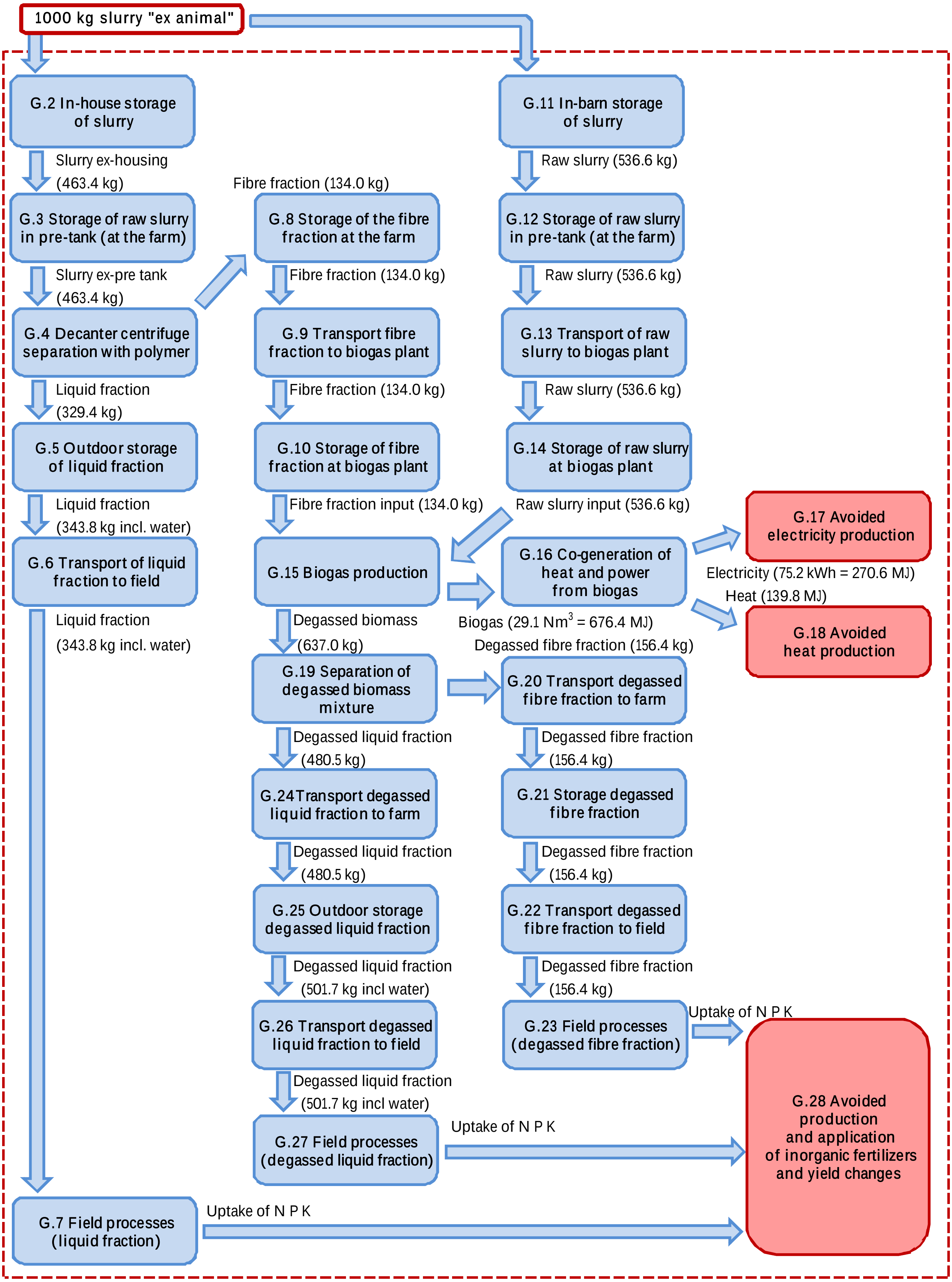
- **Section 4 : Processes G.15 to G.18**
  This section focuses on the biogas production (G.15) and the resulting heat and power co-generation (G.16). This co-generation avoids marginal electricity to be produced (G.17) and well as marginal heat (G.18).
- **Section 5 : Process G.19**
  This section describes the separation of the degassed biomass mixture output from the anaerobic digestion (G.19).
- **Section 6 : Processes G.20 to G.23**
  This section focuses on the fate of the degassed fibre fraction. After the separation, it is transported to a farm where a fertilizer rich in P is needed (G.20), stored (G.21) until it is transported to the field (G.22) to be used as a fertilizer (G.23).
- **Section 7 : Processes G.24 to G.27**
  This section focuses on the fate of the degassed liquid fraction. After the separation, it is transported back to the farm (G.24), stored (G.25) until it is transported to the field (G.26) to be used as a fertilizer (G.27).
- **Section 8: Process G.28**
  Throughout this annex, three organic fertilizers were used: a liquid fraction (G.7), a degassed liquid fraction (G.27) and a degassed solid fraction (G.23). The use of these organic fertilizers allowed to avoid inorganic fertilizer to be produced and used (G.28), which is the main focus of this section.

The scenario described in this annex has been modelled in order to include “Best Available Technology” as much as possible. The conditions considered throughout the scenario were chosen in the light of the best feasible possibilities. This applies for the technologies used as well as for the management practices. However, conservative assumptions were used in the calculation of the emissions, in order to ensure the life cycle assessment reflects the correct picture as regarding the environmental consequences of this manure management option.

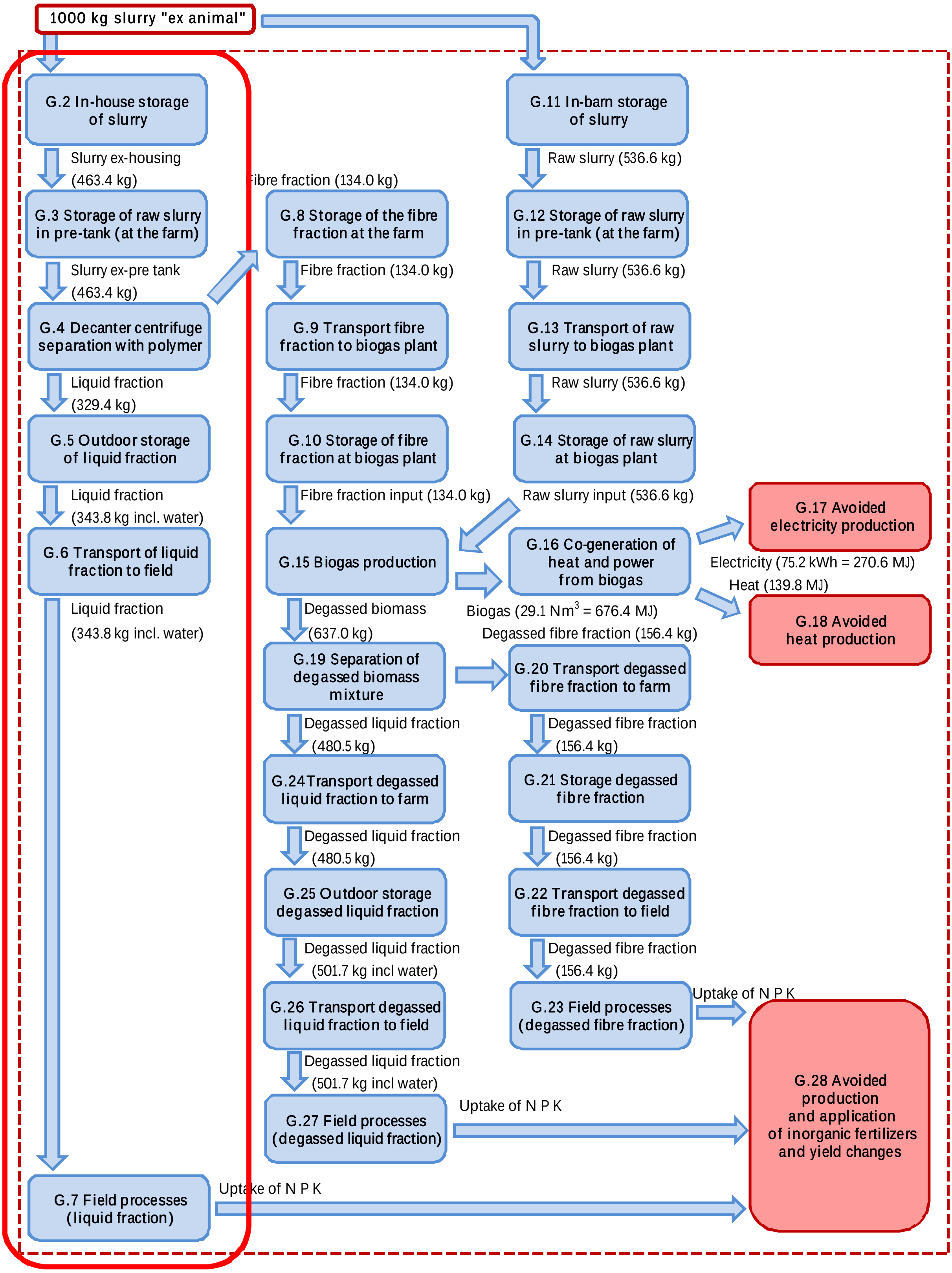
It shall also be mentioned that many possibilities could have been included as regarding the different variants in the biogas production, which could be worth another life cycle assessment themselves. For example, instead of being used for co-generation of heat and power through a biogas engine, the biogas could have been cleaned and injected directly to the natural gas grid (this possibility is however considered as a sensitivity analysis). Else, it could also have been upgraded and used as a transportation fuel. Also, the slurry is sometimes treated in a pre-treatment plant before entering the biogas plant, which is another variant not included here.

The overall flow diagram for this scenario is presented in figure G.1.

Figure G.1.
Flow diagram for biogas production based on raw slurry + fibre fraction from mechanically separated cow slurry with a decanter centrifuge and polymer addition



Processes G.2 to G.7: Raw slurry from which the fibre fraction origins: production, separation and fate of the liquid fraction



G.2 In-house storage of slurry

The assumptions and Life Cycle Inventory data for the storage of slurry in the housing units are the same as for the reference scenario (section A.2, Annex A). Accordingly, the CH_4 and N_2O emissions are calculated according to IPCC guidelines (IPCC, 2006).

For CH_4, the calculation is thus as follows: CH_4 [kg] = VS [kg] * B_0[1] * 0.67 [kg CH_4 per m^3 CH_4] * MCF[2], with the "ex-animal" VS and with MCF = 17 % (value for pit storage below animal confinement greater than 1 month, table 10.17 in IPCC 2006). The choice of a MCF value of 17 %, as explained in Annex A (section A.2), is conservative, the alternative being a MCF = 3 % if the storage is less than one month, based on IPCC (2006) tabulated values. The gap between these two alternatives MCF values is considerable. This means that the overall greenhouse gas emissions related to the in-house storage presented in this study, if compared to other studies, may be significantly higher based on the choice of this MCF value. Yet, systems need to be comparable, so the alternatives assessed hereby must be assessed as in the reference scenario.

As the in-house storage of slurry is identical to the one in the reference case, performing a sensitivity analysis with a lower MCF would only contribute to reduce the CH_4 emissions of both the present and the reference scenario by the same order of magnitude. Instead, the effect of this conservative choice for the MCF value is raised as a discussion point in the interpretation of the results. It is however acknowledged that the CH_4 emissions during in-house storage could have been estimated with an Arrehenius relationship, as proposed by Sommer et al. (2004) and Sommer et al. (2009) instead of the IPCC methodology.

For direct N_2O emissions, IPCC (2006) estimates the N_2O emissions from pit storage below animal confinements to be 0.002 kg N_2O-N per kg N "ex-animal" (uncertainty: a factor 2), based on the judgement of an IPCC expert group combined with various studies. The indirect N_2O emission corresponds to 0.01 kg N_2O–N per kg (NH_3–N + NO_X–N volatilised) (IPCC, 2006, table 11.3).

The NO-N and N_2-N emissions were calculated in the same way as in Annex A, i.e. based on the study of Dämmgen and Hutchings (2008). In their study, they assumed that the emission of nitrogen monoxide (NO) is the same as

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[1] B_0 : maximum methane producing capacity for manure produced, corresponds to 0.24 m^3 CH_4/kg VS ex-animal for dairy cows (IPCC 2006, table 10A-4)

[2] MCF: methane conversion factor (%).The MCF factor is defined in the IPCC (IPCC,1997) guidelines in chapter 4 (on page 4.9) as follows :
"Methane Conversion Factor (MCF): The MCF defines the portion of the methane producing potential (Bo) that is achieved. The MCF varies with the manner in which the manure is managed and the climate and can theoretically range from 0 to 100 per cent. Manure managed as a liquid under hot conditions promotes methane formation and emissions. These manure management conditions have high MCFs, of 65 to 90 per cent. Manure managed as dry material in cold climates does not readily produce methane, and consequently has an MCF of about 1 per cent. Laboratory measurements were used to estimate MCFs for the major manure management techniques."

the direct emission of nitrous oxide (N_2O) (measured as NO-N and N_2O-N). Furthermore, they assumed that emission of nitrogen (N_2) is three times as high as the direct emissions of nitrous oxide (N_2O) (measured as N_2-N and N_2O-N).

As regarding the total NO_x emissions ($NO_x = NO + NO_2$), it was assumed, as in Annex A, that $NO_x = NO$. This is because it has not been possible to find data on NO_2.

Ammonia emissions are estimated based on Poulsen et al. (2001), where an emission factor of 8% NH_3-N of the total N ex-animal is suggested for dairy cows in cubicle housing system with slatted floors.

Emissions of CO_2 are based on mass balances, i.e. as the total loss of carbon in the housing units minus the carbon lost as CH_4 emissions. The total loss carbon in the housing units is 5.3 kg (table A.8, Annex A), so this gives a CO_2 emission of 11.60 kg/1000 kg slurry ex-housing (see calculation in table G.1).This mass balance approach is used because the slurry composition for C was determined backwards, i.e. from the C content of ex-storage slurry through the C content of ex-housing slurry and finally ex-animal slurry. This backwards approach was used due to the availability of data. Estimating the CO_2 emissions for the in-house storage with another approach than the mass balance would therefore change the ex-housing manure composition, which is the very basis of comparison between all scenarios. Yet, in subsequent anaerobic storages of slurry, the CO_2 emissions are estimated as a function of the CH_4 emissions (i.e. sections G.5, G.15 and G.25). If the in-house CO_2 production would have been calculated in accordance with the CO_2:CH_4 ratio as described in section G.5 (i.e. 1.67 g of CO_2 is produced per g of CH_4) the CO_2 emission here would have been 4.76 kg CO_2 (1.67 kg CO_2/kg CH_4 x 2.85 kg CH_4). Compared to the actual 11.60 k g CO_2, the difference is not significant for the overall results. Accordingly, the current method for calculation of the CO_2 emission from slurry stored in the barn does not influence the overall results.

Moreover, part of the produced CO_2 from the in-house storage (and also outdoor storage) is emitted to air immediately and part of the CO_2 is dissolved in the slurry. In this life cycle assessment, it is calculated as all the CO_2 is emitted to air immediately. By calculating this way, the CO_2 will be emitted at the process that causes the CO_2, which makes the interpretation of the sources easier. Furthermore it does not change the overall result, as the overall amount of CO_2 emitted is exactly the same. The only difference is that it would have been emitted at a later stage in the life cycle chain of the slurry. The same approach has been used in Annex B, see section B.2.

Table G.1 (taken from Annex A), shows the life cycle data for the in-house storage of raw slurry.

Table G.1.
Life cycle Inventory data for storage of raw cow slurry in the housing units. All data per 1000 kg of slurry “ex-animal”. (taken from Annex A, table A.9)

	Dairy cow slurry	Comments
Input		
Slurry “ex-animal”	1000 kg	The input to this process is 1000 kg slurry “ex-animal”. This is the reference amount of slurry. The emissions are calculated relative to this.
Output		
Slurry “ex-housing”	1000 kg	Here, the output mass is the same as the input mass. Deviations due to added water and emissions are not included in the total mass, see the discussion before table A.4., section A.1.2 in Annex A.
Energy consumption		
	Not included	The energy consumption for the housing units is not included within the system boundary.
Emissions to air		
Carbon dioxide (CO_2)	11.60 kg	Estimated as total loss of C minus CH_4 emissions (given below): 5.3 kg C –(2.85 kg CH_4*[12.011/16.033]) = 3.17 kg CO2-C 3.17 kg CO2-C corresponds to 3.17 kg * (12.011 + 2 * 15.9994) / 12.011 = 11.6 kg CO2
Methane (CH_4)	2.85 kg	IPCC (2006) Tier 2 approach with MCF = 17 %, see text. CH_4 = 104.2 kg VS/1000 kg slurry * 0.24 m^3 CH_4/kg VS * 0.67 kg CH_4/m^3 CH_4 * 17 % = 2.85 kg. (VS ex-animal is from table A.2, Annex A).
Ammonia (NH_3-N)	0.550 kg	Based on Poulsen et al. (2001). For dairy cows slurry (cubicle housing with slatted floor): 8% NH3-N of the total-N “ex-animal”: 6.87 kg N/1000 kg slurry ex-animal * 8 % = 0.550 kg.
Direct emissions of Nitrous oxide (N_2O-N)	0.0137 kg	0.002 N_2O-N per kg N “ex-animal” (IPCC, 2006): 6.87 kg N/1000 kg slurry ex-animal * 0.002 = 0.0137 kg.
Indirect emissions of Nitrous oxide (N_2O-N)	0.0056 kg	0.01 kg N_2O–N per kg of (NH_3–N + NO_X–N) volatilised (IPCC, 2006, table 11.3). Ammonia and NO emissions given in this table.
Nitrogen monoxide (NO-N) (representing total NO_X)	0.0137 kg	Estimate based on Dämmgen and Hutchings (2008), consisting of assuming that NO-N = (direct) N_2O-N * 1, see text.
Nitrogen dioxide (NO_2-N)	No data	No data.
Nitrogen (N_2-N)	0.0412 kg	Estimate based on Dämmgen and Hutchings (2008), consisting of assuming that N_2-N = (direct) N_2O-N * 3, see text.
Discharges to water		
	None	Assumed to be zero, as leakages from housing systems are prohibited in Denmark.
Discharges to soil		
	None	Assumed to be zero, as leakages from housing systems are prohibited in Denmark.

G.3 Storage of slurry in pre-tank

The raw slurry ex-housing is stored in the pre-tank, and will later be directly pumped from there when transferred to the separation unit. No significant losses from the pre-tank storage as well as no water addition are assumed; it is thus consistent with section C.3 in Annex C (storage of slurry in pre-tank before separation with the Samson Bimatech technology).

The exact duration of the storage in the pre-tank is, in practice, quite variable, from a few days to a few weeks, according to the contracts farmers have with the biogas plants regarding the deliveries. According to Rosager (2009), assuming a storage duration of maximum 10 to 14 days in the pre-tank would be a reasonable, though conservative, assumption. This assumption was therefore applied in this project.

Assuming no losses may be reasonable for this duration period, but it may not be correct for a longer storage period, particularly as regarding losses of C (through CH_4 and CO_2).

In fact, Møller et al. (2004), who estimated the losses of carbon from in-house storage of both pig and cattle manure in a laboratory-scale study, reported the losses of both CO_2 and CH_4 as a function of the storage time. From the graphs presented in Møller et al. (2004), it can be seen that an emission peak (for CH_4) occurs between 0 and 20 days after excretion (storage at 15°C, for cow manure). In the case of this project, no specific storage duration was assumed for the in-house storage (it was only assumed that it is less than 1 month, see section A.2.2 of Annex A), but it appears likely that the emission peak presented in Møller et al. (2004) for CH_4 did occur during the in-house storage (i.e. before the slurry was transferred to the pre-tank). Moreover, important CH_4 emissions were considered during the in-house storage of the slurry (as a methane conversion factor of 17% was used in the calculation, see discussion in section G.2). Given these facts, it appears reasonable to assume no additional methane losses for the pre-tank storage phase.

The energy consumption related to the slurry transfer from the pre-tank through the separation unit involves the electricity for stirring in the pre-tank before pumping (1.2 kWh per 1000 kg slurry ex-housing, as in table A.10 of Annex A) and the electricity for pumping (0.5 kWh per 1000 kg slurry ex-housing, as in table A.10 of Annex A). This involves a total energy consumption of 1.7 kWh per 1000 kg slurry ex-housing.

The life cycle data for the storage of the slurry in the pre-tank are presented in table G.2. The ex pre-tank slurry composition considered is presented in table G.3 (which is identical to the ex-housing slurry of Annex A, table A.2).

Table G.2.
Life cycle Inventory data for storage of raw slurry in the pre-tank. All data per 1000 kg of slurry “ex-animal”. Dairy cow slurry.

	Dairy cow slurry	Comments
Input		
Slurry “ex-housing”	1000 kg	The input to this process is 1000 kg slurry “ex-animal”. This is the reference amount of slurry. The emissions are calculated relative to this.
Output		
Slurry “ex pre-tank”	1000 kg	Here, the output mass is the same as the output mass. Deviations due to added water and emissions are not included in the total mass, see the discussion before table A.4., section A.1.2 in Annex A.
Energy consumption		
Electricity	1.7 kWh	Electricity for stirring and pumping
Emissions to air		
Carbon dioxide (CO_2)	Negligible	Considered as negligible, see text.
Methane (CH_4)	Negligible	Considered as negligible, see text.
Ammonia (NH_3-N)	Negligible	Considered as negligible, see text.
Direct emissions of Nitrous oxide (N_2O-N)	Negligible	Considered as negligible, see text.
Indirect emissions of Nitrous oxide (N_2O-N)	Negligible	Considered as negligible, see text.
Nitrogen monoxide (NO-N) (representing total NO_X)	Negligible	Considered as negligible, see text.
Nitrogen dioxide (NO_2-N)	Negligible	Considered as negligible, see text.
Nitrogen (N_2-N)	Negligible	Considered as negligible, see text.
Discharges to water		
	None	Assumed to be zero, as leakages from housing systems are prohibited in Denmark.
Discharges to soil		
	None	Assumed to be zero, as leakages from housing systems are prohibited in Denmark.

Table G.3.
Characteristics of slurry ex pre-tank from dairy cows
Per 1000 kg of slurry ex pre-tank

	Slurry ex pre-tank
Total mass	1000 kg
Dry matter (DM)	113.2 kg
Ash content	21.5 kg
Volatile solids (VS) Of total VS: - easily degradable - heavy degradable	91.7 kg 37.5 kg 54.2 kg
Total-N (DJF, 2008)	*No data (calculated: 6.41 kg)*
Total-N in this study	6.34 kg
$NH4^+$-N	No data
Total-P	1.03 kg
Potassium (K)	5.90 kg
Carbon (C)	49.7 kg
Copper (Cu)[a)]	0.0121 kg
Zinc (Zn) [a)]	0.0234 kg
Density	1053 kg per m^3
pH	7.8

a) This is different from the value presented in table A.2 from Annex A, as an error as been made for Cu and Zn ex-housing, where the values “12.1 g Cu and 23.4 g Zn” should figure instead of “12.1 kg Cu and 23.4 kg Zn”.

G.4 Separation by a belt press separator combined with the use of polymer

G.4.1 Description of the separation technology

The separation process used in this study is the technology manufactured by Kemira water, model Kemira 808 C for cow slurry. It consists of flocculation chambers in which added polymer is mixed with the slurry; this alters the physical state of the dissolved and suspended solids and facilitates their removal by a belt press. A combination of screens and screw press is then used to finalize the separation. The polymer considered is a cationic polyacrylamide (PAA). The polymer consumption is further detailed in table G.10 (an addition of 0.60 kg per 1000 kg of slurry input in the separation is considered in this study).

G.4.2 Separation indexes and mass balances

It is assumed that the composition of the slurry leaving the pre-tank is the same as the “ex-housing” composition in the reference scenario, as it has been assumed that there are no losses or emissions during the storage in the pre-tank (section G.3). This assumption is not strictly correct due to the biological processes in the slurry during the residence time in the pre-tank, as discussed in section C.3 of Annex C.

The separation efficiencies considered are based on experimental data provided by the technology manufacturer (Kemira, year unknown a). These data are presented in table G.4. It must be emphasized that the total mass of the raw slurry do not balance the mass of the liquid fraction summed to the mass of the fibre fraction (probably due to uncertainties during the measurements).

Table G.4.
Original data from the kemira separation of cattle slurry (including the use of polymer)

	Kemira data for raw slurry before separation	Kemira data for the liquid fraction after the separation	Kemira data on the fibre fraction after the separation	Comment
Total mass	3250 tons	2700 tons	664 tons	Note that there is 3.5 % deviation for the mass balance here. Kemira do not explain this deviation. It is probably due to the measurement uncertainties.
Dry matter (DM)	8%	2%	31%	
Total-N	4.5 kg/ton	2.7 kg/ton	11 kg/ton	
Phosphorous (P)	1.2 kg/ton	0.45 kg/ton	4 kg/ton	
Potassium (K)	No data	No data	No data	

Based on the data presented in table G.4, a mass balance can be performed, as presented in table G.5.

Table G.5.
Mass balances based on the original data from the kemira separation

	Kemira data for raw slurry before separation	Kemira data on the liquid fraction after the separation	Kemira data on the fibre fraction after the separation	Total mass AFTER separation	Comment
Total mass	3250 tons	2700 tons	664 tons	2700 tons + 664 tons = 3364 tons	3.5 % deviation for the mass balance.
Dry matter (DM)	8% of 3250 tons = 260 kg	2% of 2700 tons = 54 kg	31% of 664 tons = 205.8 kg	54 kg + 205.8 kg = 259.8 kg	The deviation of the mass balance is less than 1%.
Total-N	4.5 kg/ton * 3250 tons = 14625 kg N	2.7 kg/ton * 2700 tons = 7290 kg N	11 kg/ton * 664 tons = 7304 kg N	7290 kg N + 7304 kg N = 14594 kg N	The deviation of the mass balance is less than 1%.
Phosphorous (P)	1.2 kg/ton * 3250 tons = 3900 kg P	0.45 kg/ton * 2700 tons = 1215 kg P	4 kg/ton * 664 tons = 2656 kg P	1215 kg P + 2656 kg P = 3871 kg P	The deviation of the mass balance is less than 1%.
Potassium (K)	No data	No data	No data		

From the mass balances of table G.5, it is possible to calculate the separation indexes for this separation process, as presented in table G.6. As explained in Annex F (section F.4.2), the separation index is the mass of a compound in the solid fraction divided by the mass of the compound in the original slurry before separation, e.g.

$$\text{Separation index for N (\%)} = \frac{\text{kg N in solid fraction}}{\text{kg N in slurry before separation}} * 100\%$$

Table G.6.
Calculated separation indexes for separation of cattle slurry.

	Fibre fraction	Liquid fraction
Total mass	664/3364*100% = 19.74%	2700/3364*100%= 80.26%
Dry matter (DM)	205.8/259.8*100% = 79.2%	54/259.8*100 = 20.8%
Total-N	7304/14594*100% = 50.0%	7290/14594*100% = 50.0%
Phosphorous (P)	2656/3871*100% = 68.6%	1215/3871*100% = 31.4%
Potassium (K)	20% a)	80% a)

a) No data has been available. Rough estimate based on data from Kemira technology model 812 P (Kemira, unknown year b)

In this project, the separation efficiencies will be based the data shown in table G.6, except for the total mass. Due to the lower content of water in the slurry (as mentioned in Annex F), it has been necessary to adjust the separation index for the total mass of the slurry in order to create a realistic fibre fraction. In order to do so, it was assumed that the DM of the solid fraction coming out of the separator would remain approximately constant independently of the water content of the raw slurry. Based on this, the total mass of fibre fraction can be evaluated, and thereby the separation index for the total mass.

The amount of DM in the raw ex-housing cow slurry is 113.2 kg per 1000 kg slurry ex-housing, as presented in table G.2. This is the input slurry into the separation process. Table G.6 shows that the separation index for the DM in the fibre fraction is 79.2 %. This means that, for an input of 1000 kg slurry ex-housing, there is 89.65 kg of DM in the fibre fraction[3]. Yet, according to the data presented in table G.4, the DM content of the fibre fraction is 31 %, which means, for 1000 kg of fibre fraction, a mass of 310 kg DM. Based on this, the amount of fibre fraction corresponding to 89.65 kg DM can be calculated, and this gives 289.19 kg fibre fraction per 1000 kg of slurry input[4]. The balance therefore corresponds to the liquid fraction, i.e. 710.81 kg liquid fraction[5]. The mass separation index considered for this project is thus 28.919 % for the fibre fraction, and 71.081 % for the liquid fraction.

Table G.7 summarizes the separation indexes used for this study. As there is no data for Cu and Zn in table G.4 to G.6, the separation efficiencies for Cu and Zn were taken from Møller et al. (2007b) (data from screw press, with cattle slurry no.3). Since no polymer addition is involved in the study performed by Møller et al. (2007b), these efficiencies may be lower as those involved in the actual study, but it is yet a better approximation than simply ignoring Cu and Zn for the rest of the analysis.

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[3] 113.2 kg DM/1000 kg slurry ex-housing * 79.2% = 89.65 kg DM in the fibre fraction per 1000 kg slurry ex-housing.

[4] (89.65 kg DM/1000 kg slurry ex-housing) * (1000 kg fibre fraction / 310 kg DM) = 289.19 kg fibre fraction per 1000 kg slurry ex-housing.

[5] 1000 kg raw slurry – 289.19 kg fibre fraction = 710.81 kg liquid fraction.

Table G.7.
Separation indexes considered in this study – separation of cattle slurry with kemira 808C technology and polymer addition

	Fibre fraction	Liquid fraction
Total mass	28.919 %	71.081 %
Dry matter (DM)	79.2 %	20.8 %
Total-N	50.0%	50.0 %
Phosphorous (P)	68.6%	31.4 %
Potassium (K)	20%	80 %
Carbon (C)[a)]	79.2 %	20.8 %
Cooper (Cu)	9.0 %	91 %
Zinc (Zn)	11.1 %	88.9 %

a) No data available. Assumed to be the same as DM.

The mass balances calculations in order to determine the composition of both fractions after the separation are presented in table G.8.

Table G.8
Mass balances for separation of slurry from **Dairy cows.**
Per 1000 kg of slurry “ex pre-tank”.

	Amount in slurry ex pre-tank BEFORE separation (from table G.3)	Separation index (i.e. percentage transferred to fibre fraction) (from table G.7)	Mass Balance: Amount transferred to the fibre fraction	Mass balance: Amount transferred to the liquid fraction	Composition of the fibre fraction AFTER separation Calculation: Amount in Fibre fraction * 1000 / 289.19 kg	Composition of liquid fraction AFTER separation Calculation: Amount in Liquid fraction * 1000 kg / 710.81 kg
	[per 1000 kg ex pre-tank]		[per 1000 kg ex pre-tank]	[per 1000 kg ex pre-tank]	[kg per 1000 kg fibre fraction]	[kg per 1000 kg liquid fraction]
Total mass	1000 kg slurry ex-housing	28.919%	289.19 kg	1000 kg – 289.19 kg = 710.81 kg	1000 kg Fibre fraction	1000 kg liquid fraction
Dry matter (DM)	113.2 kg	79.2%	113.2 kg *79.2% = 89.654 kg	113.2 kg *(100-79.2)% = 23.546 kg	310.0 kg	33.1 kg
Total-N	6.34 kg	50.0%	6.34 kg *50.0% = 3.17 kg	6.34 kg *(100-50.0)% = 3.17 kg	10.96 kg	4.46 kg
Total-P	1.03 kg	68.6%	1.03 kg *68.6% = 0.7066 kg	1.03 kg *(100-68.6)% = 0.3234 kg	2.44 kg	0.455 kg
Potassium (K)	5.90 kg	20%	5.90 kg *20% = 1.18 kg	5.90 kg *(100-20)% = 4.72 kg	4.08 kg	6.64 kg
Carbon (C)	49.7 kg	79.2%	49.7 kg *79.2% = 39.362 kg	49.7 kg *(100-79.2)% = 10.338 kg	136.11 kg	14.54 kg
Copper (Cu)	0.0121 kg	9.0%	0.0121 kg *9.0% =0.00109 kg	0.0121 kg *(100-9.0)% = 0.01101 kg	0.0038 kg	0.0155 kg
Zinc (Zn)	0.0234 kg	11.1%	0.0234 kg *11.1% = 0.00260 kg	0.0234 kg *(100-11.1)% = 0.02080 kg	0.0090 kg	0.0293 kg

The mass balances of the separation of the slurry used in this study versus the separation of the slurry used by Kemira (from which the separation indexes were derivated, table G.4) are compared in table G.9.

Table G.9
Comparison of the mass balance separation of the cow slurry used in this study with the cow slurry from the Kemira data in table G.4

	Norm Data Dairy cow slurry BEFORE separation	Kemira dairy cow slurry sample BEFORE separation	Norm Data FIBER fraction	Kemira slurry sample FIBER fraction	Norm Data LIQUID fraction	Kemira slurry sample LIQUID fraction
	[per 1000 kg slurry]	[per 1000 kg slurry]	[per 1000 kg fibre fraction]	[per 1000 kg fibre fraction]	[per 1000 kg liquid fraction]	[per 1000 kg liquid fraction]
Total mass distribution	100%	100%	28.92%	19.74%	71.08%	80.26%
Dry matter (DM)	113.2 kg	80 kg	310.0 kg	310.0 kg	33.1 kg	20 kg
Total-N	6.34 kg	4.5 kg	10.96 kg	11 kg	4.46 kg	2.7 kg
Total-P	1.03 kg	1.2 kg	2.44 kg	4 kg	0.455 kg	0.45 kg
Potassium (K)	5.90 kg	No data	4.08 kg	No data	6.64 kg	No data
Carbon (C)	49.7 kg	No data	136.11 kg[a]	No data	14.54 kg[a]	No data
Cooper (Cu)	0.0121 kg	No data	0.0038 kg[b]	No data	0.0155 kg[b]	No data
Zinc (Zn)	0.0234 kg	No data	0.0090 kg[b]	No data	0.0293 kg[b]	No data

a) Calculated assuming that the separation index was the same as DM.
b) Calculated using separation indexes from Møller et al. (2007b).

When comparing the separation of the cow slurry used in this study and the “Kemira cow slurry sample” in table G.9, it can be seen that:

- The Kemira dairy cow slurry samples are in general more diluted than the cow slurry used in this study BEFORE the separation. It contains relatively more water.
- The liquid fraction from the Kemira dairy cow slurry is more diluted than the liquid fraction obtained from the slurry in this study. It reflects the difference of water content between the slurries before the separation.

G.4.3 Polymer addition

As described in G.4.1, the separation process includes the use of a polymer (cationic polyacrylamide). The polymer data is shown in table G.10 below.

Table G.10.
Data on the polymer used for the separation.

Polymer consumption	
Mass of polymer consumed (cationic polyacrylamide)	0.60 kg per 1000 kg slurry input in the separation process
Polymer commercial name	
Superfloc® C-2260 Flocculant	
Polymer composition	
Citric acid	3%[a]
Unspecified mineral oil distillate (acrylamide)	25%[a]
Ethoxylated alcohols (C12-16)	4%[a]
Water	68%[b]

a) From the “Sikkerhedsdatablad”
b) Calculated as the rest

Polyacrylamide polymers (PAM) are widely investigated in the scientific literature as regarding their performance in solid-liquid separation of slurries (e.g. Martinez-Almela and Barrera, 2005; Campos et al., 2008; Vanotti et al., 2002; Vanotti et al., 2005; González-Fernández et al., 2008; Hjorth et al., 2008). Though the polyacrylamide polymer can be defined as many units of the monomer acrylamide, the chemical nature of the polymer and the monomer is highly different (Caulfield et al., 2002). While polyacrylamide is considered as a relatively safe material, the toxicity of acrylamide monomer is a major concern (El-Mamouni et al., 2002), this component being known to affect the central and peripheral nervous system (ICON, 2001). PAM can be charged positively (anionic), negatively (cationic) or non-charged (non-ionic) (Barvenik, 1994). Concerns regarding the toxicity of cationic PAM (as used in this project) have however been expressed in the literature (e.g. Entry et al., 2002; Barvenik, 1994), and flow-through conditions showed that water-soluble cationic polymers present more long-term toxicity than they do under static conditions (Goodrich et al., 1991).

Once the PAM degrades to acrylamide monomer, the monomer is then subjected to rapid degradation in which it is decomposed to ammonia and to acrylic acid ($CH_2CHCOOH$), which in turn is degraded to CO_2 and water (ICON, 2001). Because of the rapid degradation of the acrylamide monomer, it is reported that it is unlikely to find this toxic product in the environment because of PAM degradation (Sojka et al., 2007).

Campos et al. (2005) investigated if PAM degradation takes place during the anaerobic digestion of solid fractions obtained from pig slurry separated with and without the use of PAM. The authors concluded from the results of their biodegradability study that PAM is not significantly biodegradable by anaerobic microorganisms and is not toxic for anaerobic microorganisms, as no significant differences were observed between the maximum methanogenic activity of the different treatments investigated (different concentration of PAM in the solid fractions). Similarly, Martinez-Almela and Barrera (2005) as well as Gonzalez-Fernández et al. (2008) also concluded that PAM residues do not contribute to toxicity of the anaerobic digestion and do not affect the methane production. Recalcitrance of PAM to microbial degradation under both aerobic and anaerobic conditions was also observed by El-Mamouni et al. (2002).

In this study, it was therefore considered that all the polymer used during the separation will end up in the field, through the application of the degassed fibre fraction as a fertilizer. The fate of the polymer in the soil is further detailed in section G.23.

G.4.4 Energy consumption

Due to lack of data, it has been assumed that the energy consumption for the separation is the same as for pig slurry in Annex F (section F.4.4), i.e. 2.184 kWh per 1000 kg slurry input, as shown in table G.11.

Table G.11.
Energy consumption for the separation process

Energy consumption	
Electricity needed for separation	2.184 kWh per 1000 kg slurry input

G.4.5 Material consumption

The data for the material consumption related to the separation equipment were assumed to be the same as for Annex F (section F.4.5) and are presented in table G.12.

Table G.12
Material consumption for the separation equipment

Materials	Weight of material in plant	Estimated life time	Amount of slurry per year [m^3 slurry per year]	Amount of slurry in a life time [m^3 slurry in a life time]	Weight [per 1000 kg slurry]
Separator					
Steel in container	2 300 kg	30 years	15000 m^3 / y	450000 m^3	5 g
Steel in compressor	2 700 kg	30 years	15000 m^3 / y	450000 m^3	6 g
Copper in cables	10.5 kg	30 years	15000 m^3 / y	450000 m^3	0.023 g
Electronics	0.5 kg - Assumed as 0.5 laptops	Assumption: 5 years	15000 m^3 / y	75000 m^3	6.67 E-6 laptops
Screw in screw press					
Steel	50 kg	1 years	15000 m^3 / y	15000 m^3	3.3 g
Filter for screw press					
Steel	6.5 kg	0.5 year	15000 m^3 / y	7500 m^3	0.86 g

G.4.6 Overall life cycle data for separation

Table G.13 presents the overall lifecycle data for the separation process. It should be highlighted that no data as regarding the emissions occurring during the separation process has been found. This lack of data is particularly critical as regarding ammonia emissions, which are likely to occur given the volatile nature of ammonia. Emissions of ammonia at this stage would change the total N content of the two fractions. As no data were available to make any reasonable estimate, no emissions will be considered to occur during the separation. Yet, it appears reasonable to assume that all the emissions likely to occur during the separation are occurring in later stages anyway, so considering them at this stage or at later stages does not change the overall results.

Table G.13.
Life cycle data for separation (decanter centrifuge + polymer). Data per 1000 kg slurry (ex pre-tank).

	Dairy cow slurry	Comments
Input		
Slurry (ex pre-tank)	1000 kg	Slurry directly from the pre-tank. This is the reference amount of slurry, i.e. the emissions are calculated relative to this.
Output		
Fibre fraction	289.19 kg	
Liquid fraction	710.81 kg	
Energy consumption		
Electricity	2.184 kWh	See table G.11
Material consumption		
Separation equipment	included	See table G.12
Consumption of chemicals		
Polymer added during the separation	0.60 kg	Polymer composition detailed in table G.10
Emissions to air		
Carbon dioxide (CO_2)		No data
Methane (CH_4)		No data
Non-methane volatile organic compounds (NMVOC)		No data
Ammonia (NH_3-N)		No data.
Nitrous oxide (N_2O-N)		No data
Nitrogen oxides (NO_X)		No data
Nitrogen monoxide(NO)		No data
Nitrogen(N_2)		No data
Particulates		No data
Hydrogen sulphide (H_2S)		No data
Sulphur dioxide (SO_2)		No data
Odour		No data
Emissions to water		
		No emissions to water

G.5 Outdoor storage of the liquid fraction

G.5.1 General description

The liquid fraction is stored in an outdoor concrete tank, as for the dairy cow slurry in the reference scenario (Annex A, section A.3). In the reference scenario, it was assumed that a natural crust cover is formed by itself during the storage of cow slurry. The formation of such a natural floating cover is due to the fibrous material contained in the slurry. As most of this material has been removed by the separation, the liquid fraction will be covered with a floating layer consisting of 2.5 kg of straw per 1000 kg slurry stored, as in Annex F (section F.5.1). Yet, because straw is regarded as a waste product from cereal production (rather than a co-product), the life cycle data of straw production are not included in this study.

G.5.2 Addition of water

Water will be added in the liquid fraction during storage through precipitations. The amount of precipitations is the same as in Annex A, i.e. a total of 44 kg of water.

G.5.3 Electricity consumption

The electricity for pumping and stirring is taken from table A.10 (Annex A) and further adjusted by a reduction factor. This is because the electricity consumption data presented in Annex A are for raw slurry. Yet, the separated liquid fraction can be anticipated to offer much less resistance when stirring or pumping than does the slurry, therefore resulting in smaller energy consumption. Therefore, the total energy consumption, as calculated from data in Annex A, will be multiplied by 0.5. This is a rather rough estimate, but as the energy consumption from pumping and stirring has had a rather insignificant contribution on the overall environmental impacts in Wesnæs et al. (2009) (figure 3.3), the magnitude of the uncertainty does not matter so much for this parameter.

The electricity consumption involves : the consumption for stirring when straw is added (1.2 kWh per 1000 kg slurry), the consumption for stirring (1.2 kWh per 1000 kg) and pumping (0.5 kWh per 1000 kg slurry), before application to the field. This gives an electricity consumption of 2.9 kWh per 1000 kg liquid fraction, on which a factor of 50 % is applied, which results in an electricity consumption of 1.45 kWh per 1000 kg liquid fraction.

G.5.4 Emissions of CH_4

Dinuccio et al. (2008) measured CH_4-C emissions from a mechanically separated liquid fraction (from raw cattle slurry) corresponding to 2.19 and 1.55 % of the VS for slurry stored during 30 d at 5 °C and 25 °C respectively. Amon et al. (2006) measured the CH_4 emissions from a mechanically separated liquid fraction (screw sieve separator) obtained from dairy cows. The liquid fraction was stored in a wooden-covered concrete tank during 80 days. The emissions measured by Amon et al. (2006) amount to 1833.0 g CH_4 per m^3 liquid fraction, corresponding to a reduction of approximately 55 % as compared to the emissions from their control raw slurry stored in similar facilities.

For this project, it has been decided to calculate the CH_4 emissions based on the IPCC methodology[6], but by using the VS content of the separated liquid fraction (the VS being calculated with the hypothesis that VS = DM * 80 %). This was also the approach used in Annex F. This gives a CH_4 emission of 0.426 kg per 1000 kg of liquid separated fraction (i.e. 80 % * 33.1 kg DM per 1000 kg liquid fraction * 0.24 * 0.67 * 10 % = 0.426 kg).

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[6] According to IPCC (2006), the methane emission can be calculated as:
CH_4 [kg] = VS [kg] * B_0 * 0.67 [kg CH_4 per m^3 CH_4] * MCF
The VS amount is “ex-animal” and B_0 = 0.24 m^3 CH_4 per kg VS for dairy cows (IPCC, 2006, Table 10A-4). The MCF value used is 10 % (for liquid slurry with natural crust cover, cool climate, in table 10-17 of IPCC (2006)). This is also the MCF recommended under Danish conditions by Nielsen et al. (2009).

This represents the highest emission potential, as not all the VS will contribute significantly to CH_4 emissions. In fact, the heavily degradable portion of the VS is recalcitrant to microbial degradation (Sommer et al., 2009). Yet, no information is available in the literature in order to assess the portion of easily and heavily degradable VS in both liquid and solid fractions of separated slurry (Sommer et al., 2009). This means that, with the actual status of data availability, it is not possible to reflect the better performance of some separation technologies as regarding their efficiency in separating the easily degradable VS in the solid fraction and heavily degradable VS in the liquid fraction. Separating the easily degradable VS out of the liquid fraction is desirable, given the anaerobic conditions of the liquid fraction favouring their degradation into CH_4 and CO_2.

The CH_4 emissions estimated in this project may therefore slightly overestimate the actual magnitude of emissions occurring during the storage of the separated liquid. On the other hand, the effect of the straw cover, which represents an additional C source for methanogens, was not accounted for, in conformity with the reference scenario. Therefore, it is assumed that these effects are overall counterbalanced and that the CH_4 emissions calculated as described above give a fair picture of the emissions occurring in reality.

The value of 0.426 kg CH_4 emissions per 1000 kg of liquid fraction used in this study represents a reduction of 75 % as compared to the emissions occurring during storage of raw slurry (which was 1.68 kg CH_4 per 1000 kg slurry ex-housing, table A.11, Annex A), which is a little higher than the reductions reported in the literature. This is due to the better separation efficiency of total VS of the separation technology used in this study.

G.5.5 Emissions of CO_2

As in Annex F, emissions of CO_2 were estimated as a function of the methane emissions. This is the approach used throughout this study for estimating CO_2 emissions in processes where slurry is kept in anaerobic conditions (e.g. G.5 and G.25)

The ratio between CO_2 and CH_4 emitted during anaerobic degradation was estimated based on the Buswell equation (Symons and Buswell, 1933), as presented in equation (1):

$$C_nH_aO_b + \left(n - \frac{a}{4} - \frac{b}{2}\right) H_2O \rightarrow \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right) CH_4 + \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4}\right) CO_2 \quad (1)$$

The organic components making up the VS in slurry and their relative amount in cow slurry were taken from Sommer et al. (2009), and are presented in table G.14.

Table G.14
Organic components constituting the VS in slurry and their relative amount in cow slurry (adapted from Sommer et al., 2009).

Organic component	Formula	Relative amount in cow slurry (%)
VS easily degradable		
VS lipid	$C_{57}H_{104}O_6$	7.7
VS protein	$C_5H_7O_2N$	16.8
VS VFA	$C_2H_4O_2$	4.0
VS carbohydrates easily degradable	$C_6H_{10}O_5$	41.5
VS heavily degradable		
VS carbohydrates heavily degradable	$C_6H_{10}O_5$	30.1
TOTAL		100.1

Based on equation (1) and table G.14, the ratio between the number of moles of CO_2 and CH_4 from the full degradation of the easily degradable VS in the slurry can be calculated, as presented in table G.15. In table G.14, it can be noticed that the sum of the relative amount of the different organic components in cow slurry correspond to 100.1 % instead of 100 %, which may be due to a rounding error. For the calculations in this study, it is assumed that the error was for the heavily degradable carbohydrates (i.e. 30.0 % instead of 30.1 %).

Table G.15
Calculation of the ratio between the number of moles of CO_2 versus CH_4 resulting from the degradation of the easily degradable VS in the cow slurry

Organic component	Unit	CH_4	CO_2
VS lipid (1 mol)	[moles of CH_4 and CO_2 from the degradation of 1 mol VS lipid]	40 moles	17 moles
	[weight for VS lipid in cow slurry, table G.14]	7.7 %	7.7 %
	[moles of CH_4 and CO_2 from the degradation of 1 mol VS lipid as weighted for the cow slurry]	**3.08 moles**	**1.31 moles**
VS protein (1 mol)	[moles of CH_4 and CO_2 from the degradation of 1 mol VS protein]	2.9 moles	2.1 moles
	[weight for VS protein in cow slurry, table G.14]	16.8 %	16.8 %
	[moles of CH_4 and CO_2 from the degradation of 1 mol VS protein as weighted for the cow slurry]	**0.48 moles**	**0.36 moles**
VS VFA (1 mol)	[moles of CH_4 and CO_2 from the degradation of 1 mol VS VFA]	1 mole	1 mole
	[weight for VS VFA in cow slurry, table G.14]	4.0 %	4.0 %
	[moles of CH_4 and CO_2 from the degradation of 1 mol VS VFA as weighted for the cow slurry]	**0.04 moles**	**0.04 moles**
VS carbohydrates easily degradable (1 mol)	[moles of CH_4 and CO_2 from the degradation of 1 mol VS carbohydrates easily degradable]	3 moles	3 moles
	[weight for VS carbohydrates easily degradable in cow slurry, table G.14]	41.5 %	41.5 %
	[moles of CH_4 and CO_2 from the degradation of 1 mol VS carbohydrates easily degradable as weighted for the cow slurry]	**1.25 moles**	**1.25 moles**
SUM (moles of CH_4 and CO_2 as weighted for the cow slurry)		4.85 moles	2.96 moles
Ratio CO_2/CH_4		0.61 moles CO_2 per mole CH_4	

The ratio of 0.61 moles of CO_2 per mole of CH_4 calculated in table G.15 means that an amount of 1.67 g of CO_2 is produced per g of CH_4[7]. This estimate will be used in order to estimate the CO_2 emissions from the various slurry types involved in this study when slurry is kept in anaerobic conditions.

As mentioned in section G.2, part of the produced CO_2 from the outdoor storage is emitted to air immediately and part of the CO_2 is dissolved in the slurry. However, in this life cycle assessment, it is calculated as all the CO_2 is emitted to air immediately, which makes the interpretation of the sources easier, as detailed in section G.2.

G.5.6 Emissions of NH_3

In this project, the ammonia emissions are calculated using the same assumption as for the reference scenario: According to Poulsen et al. (2001), the emission of NH_3–N is 2% of the total-N in the slurry “ex-housing” (i.e. “ex-separation” in the present case). This corresponds to NH_3–N emissions of 0.0892 kg per 1000 kg of separated liquid.

G.5.7 Emissions of N_2O, NO-N and N_2-N

In the reference scenario, the direct N_2O emissions for storage were based on IPCC guidelines (IPCC, 2006). However, the IPCC methodology does not provide any emission factor for storage of separated liquid fraction. Accordingly, the direct N_2O emissions were estimated relative to the emissions in the reference scenario, adjusted with the different N content. The content of total-N “ex-separation” is 4.46 kg/1000 kg liquid fraction (table G.8). The content of total-N in the reference slurry is 6.34 kg per 1000 kg slurry ex-housing (table A.2, Annex A). The direct N_2O emissions in the reference scenario were 0.034 kg N_2O-N per 1000 kg slurry ex-housing (table A.11, Annex A). Therefore, the direct N_2O-N emissions are calculated as: 0.034 kg N_2O-N * (4.46/ 6.34) = 0.0239 kg N_2O-N per 1000 kg liquid fraction. This is also a rough estimate. Yet, it is acknowledged that the N_2O emissions may in fact be lower than this estimate due to the lower DM content in the liquid fraction (and thereby a lower potential for easily converted VS content).

The NO-N and N_2-N emissions were calculated in the same way as in Annex A, i.e. based on the study of Dämmgen and Hutchings (2008). In their study, they assumed that the emission of nitrogen monoxide (NO) is the same as the direct emission of nitrous oxide (N_2O) (measured as NO-N and N_2O-N). Furthermore, they assumed that emission of nitrogen (N_2) is three times as high as the direct emissions of nitrous oxide (N_2O) (measured as N_2-N and N_2O-N).

As regarding the total NO_X emissions ($NO_X = NO + NO_2$), it was assumed, as in Annex A, that NO_X = NO. This is because it has not been possible to find data on NO_2.

Therefore, this means that the NO-N emissions (and thereby the NO_X-N emissions) correspond to 0.0239 kg per 1000 kg liquid fraction and the N_2-N emissions correspond to 0.0717 kg per 1000 kg liquid fraction.

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[7] Calculated as: (0.61 moles CO_2/mole CH_4) * (1 mole CH_4/16.043 g CH_4) * (44.099 g CO_2/mole CO_2) = 1.67 g CO_2/g CH_4.

The indirect N_2O-N emissions can be calculated as described by IPCC guidelines (IPCC, 2006), i.e. as 0.01 * (NH_3-N + NO_X-N). This gives indirect N_2O-N emissions of 0.00113 kg per 1000 kg liquid fraction.

G.5.8 Life cycle data and mass balances for storage of liquid fraction

Table G.16 summarizes the LCA data for the storage of liquid fraction and presents the comparison with the storage emissions in Annex A. It must be emphasized that 1000 kg liquid fraction do ***not*** correspond to 1000 kg slurry ex-animal, so the values of Annex A versus Annex G are not directly comparable. Values from Annex A were only included since they were needed for the calculation of some of the emissions. For CO_2, values from Annex A are presented as they were calculated, and their equivalent is presented in parenthesis if they would have been calculated according to the ratio between CH_4 and CO_2, as explained in section G.5.5.

Table G.17 presents the mass balance of the liquid fraction in order to establish its composition after the storage. In this table, it can be noticed that the change of DM is estimated as the losses of N and C. It is acknowledged that this is a rough estimation, as other elements of greater molecular weight may also be lost (e.g. dissolved O_2). The estimated DM change shall therefore be seen as a minimum change, the actual DM change may in fact be greater than the one taken into account in this study.

Table G.16.
Life cycle data for storage of the liquid fraction. All data per 1000 kg of liquid fraction “ex-separation”.

	Reference cow slurry (scenario A)	Liquid fraction (dairy cow slurry) (scenario G)	Comments
Input			
Liquid fraction “ex-separation”		1000 kg	The emissions are calculated relative to this.
Slurry “ex-housing”	1000 kg		
Water	44 kg	44 kg	
Concrete slurry store	Included	Included	As in scenario A.
Cut straw		2.5 kg	As straw is regarded as a waste product from cereal production (rather than a co-product), the life cycle data of straw production are not included.
Output			
Slurry “ex-storage”	1044 kg	1044 kg	
Energy consumption			
Electricity		1.45 kWh	Electricity for pumping and stirring (see text).
Emissions to air			
Carbon dioxide (CO_2)	4.21 kg (if calculated as in Annex G :2.81 kg)	0.71 kg	Calculated from CH_4 emissions: kg CO_2 = kg CH_4 * 1.67 (see text).
Methane (CH_4)	1.68 kg	0.426 kg	Based on IPCC methodology (IPCC, 2006), but with VS of separated liquid fraction, see text.
Ammonia (NH_3-N)	0.13 kg	0.0892 kg	NH_3-N = 2% of the total-N in the liquid fraction “ex-separation”, see text.
Direct emissions of Nitrous oxide (N_2O-N)	0.034 kg	0.0239 kg	Evaluated based on reference slurry emissions, adjusted with relative total N ratios (see text).
Indirect emissions of Nitrous oxide (N_2O-N)	0.0016 kg	0.00113 kg	0.01 kg N_2O–N per kg (NH_3–N + NO_X–N) volatilised (IPCC, 2006, table 11.3), see text.
Nitrogen monoxide (NO-N) (representing total NO_X)	0.034 kg	0.0239 kg	Estimate based on Dämmgen and Hutchings (2008), consisting of assuming that NO-N = (direct) N_2O-N * 1, see text.
Nitrogen dioxide (NO_2-N)	No data	No data	No data
Nitrogen (N_2-N)	0.10 kg	0.0717 kg	Estimate based on Dämmgen and Hutchings (2008), consisting of assuming that N_2-N = (direct) N_2O-N * 3
Discharges to soil and water			
	None	None	Assumed to be none, as leakages from slurry tanks are prohibited in Denmark

Table G.17.
Mass balances for storage of liquid fraction after separation

	Composition of liquid fraction AFTER separation and BEFORE storage (from table G.8) [kg per 1000 kg liquid fraction]	Mass balance: Change during storage of liquid fraction [kg]	Mass balance: Amount after storage of liquid fraction [kg]	Composition of liquid fraction AFTER storage [kg per 1000 kg liquid fraction AFTER storage]
Total mass	1000 kg	44 kg	1044 kg	1000 kg
Dry matter (DM)	33.1 kg	- 0.722 kg c)	32.4 kg	31.03 kg
Total-N	4.46 kg	- 0.209 kg a)	4.25 kg	4.07 kg
Total-P	0.455 kg	No change	0.455 kg	0.436 kg
Potassium (K)	6.64 kg	No change	6.64 kg	6.36 kg
Carbon (C)	14.54 kg	- 0.513 kg b)	14.03 kg	13.44 kg
Copper (Cu)	0.0155 kg	No change	0.0155 kg	0.0148 kg
Zinc (Zn)	0.0293 kg	No change	0.0293 kg	0.0281 kg

[a] Changes in total N: 0.0892 kg NH_3-N + 0.0239 kg N_2O-N + 0.0239 kg NO-N + 0.0717 kg N_2-N = 0.209 kg N

[b] Changes in total C: 0.71 kg CO2 * 12.011 [g/mol] /44.01 [g/mol] + 0.426 kg CH4 * 12.011 [g/mol] /16.04 [g/mol] = 0.513 kg C

[c] The change in DM is assumed to be identical to the sum of the loss of N and C

G.6 Transport of the liquid fraction to the field

The transport of the liquid fraction to field is assumed to be identical to the transport of the untreated slurry in Annex A. Accordingly, the same assumptions have been applied.

This means that the process “Transport, tractor and trailer” from the Ecoinvent database (Nemecek and Kägi, 2007, p.204) has been used, for a distance of 10 km. This includes, among others, the construction of the tractor and the trailer. As the transport by trucks (instead of by tractor with a trailer) is required by law in Denmark when the slurry is transported for distances greater than 10 km, Wesnæs et al. (2009) carried out a sensitivity analysis with a transportation distance of 32 km (involving transport by truck). Yet, they found that the transport distance of slurry from the storage to the field had no significance on the environmental impacts they assessed. Therefore, the transport distance from storage to field is fixed to 10 km in the present project.

G.7 Field processes (liquid fraction)

G.7.1 General description

As in Annex A, the data from the Ecoinvent process “Slurry spreading, by vacuum tanker” (Nemecek and Kägi, 2007, p.198) were used for the emissions related to spreading equipment “consumption”. This includes the construction of the tractor and the slurry tanker, as well as the diesel consumption. The diesel consumption due to the use of the “tanker” in the Ecoinvent process was adjusted to 0.4 litres of diesel per 1000 kg of slurry, based on Kjelddal (2009) (the same as in Annex A).

G.7.2 Emissions of CH_4 and CO_2

The CH_4 emissions on the field are assumed to be negligible, as the formation of CH_4 requires an anaerobic environment, which is, under normal conditions, not the case in the top soil.

CO_2 emissions and C-binding in the soil are modelled by the dynamic soil organic matter model C-TOOL (Petersen et al., 2002; Gyldenkærne et al., 2007). The development in organic soil N is modelled by assuming a 10:1 ratio in the C to N development.

G.7.3 Emissions of NH_3

The NH_3-N emissions ***during application*** were calculated as in the reference scenario, i.e. 0.5 % of the NH_4^+-N "ex-storage". This is based on Hansen et al. (2008). Yet, Hansen et al. (2008) calculated NH_4^+-N "ex-storage" as 58 % of the total N (instead of 60 % as assumed in this study). In this specific case, because the NH_3-N emissions are calculated based on Hansen et al. (2008), the NH_4^+-N will be evaluated with the figures presented by Hansen et al. (2008), as it was done in Annex A.

According to Hansen et al. (2008), the ammonia volatilization from the liquid fraction from separated slurry applied to fields is reduced significantly in the period ***after application*** – in the order of 50%. The explanation given by Hansen et al. (2008) is that the dry matter in the liquid fraction is normally less than 3% which means that the liquid fraction infiltrates very fast in the soil, so less ammonia is likely to volatilize as compared to untreated slurry. Measurements were made on mechanically separated slurry (untreated and degassed slurry), and the liquid fraction and control slurry were applied by trail hoses. The measurements showed that the ammonia emissions were reduced by approximately 50% (Hansen et al., 2008) for the liquid fraction. Accordingly, a reduction of 50 % was used for ammonia emissions (after application) in this project, as compared to the ammonia emissions occurring in the reference scenario. Consequently, the emissions were first calculated with the methodology presented in Annex A (section A.5.3) and the result of this was multiplied by 50 %.

In Annex A, an area and slurry-N weighted average of all the NH_3-N losses involved in the crop rotation defined for the "dairy cow" scenario was performed. This resulted in a loss of 0.217 kg NH_3-N per kg TAN-N in the cow slurry (a loss that includes the emissions during application, so they have to be deduced). Assuming that the TAN (NH_3+NH_4^+), at the liquid fraction pH, corresponds to NH_4^+ only, and evaluating NH_4^+-N as 58 % of the total N (as this estimation is also based on the study of Hansen et al., 2008), it is possible to estimate the NH_3-N emissions after application.

G.7.4 Emissions of N_2O and NO_X-N and N_2-N

Direct and indirect N_2O emissions as well as emissions of NO_X-N were calculated as in the reference scenario (section A.5.3 and A.5.4 in Annex A). This means that the direct emissions of N_2O-N are evaluated as 0.01 kg N_2O-N per kg N in the ex-storage liquid fraction (table 11.1 in IPCC (2006)). Yet, it is acknowledged that this may overestimate the N_2O emissions occurring from the spreading of the liquid fraction, as the C/N ratio of the liquid fraction is lower than the C/N ratio of the non-separated slurry. In fact, according to Møller et al. (2007c), the centrifugal separation mainly transfers the organic N to the solid fraction, while the dissolved NH_4^+ goes in the liquid fraction. A higher NH_4-N content involves more N in a form directly available for plants. This means that less N shall be available to microorganisms for nitrification (where NO_3^- is formed), and thus, the potential for denitrification (where NO_3^- is reduced to N_2O, and subsequently to N_2) is reduced. According to Amon et al. (2006), a lower C/N ratio also reduces the potential for N immobilisation in the soil N pool, and thereby the availability of N for denitrification.

The indirect N_2O-N emissions ***due to ammonia and NO$_x$*** are evaluated as 0.01 kg N_2O-N per kg of (NH_3 + NO_x) volatilized. The indirect N_2O-N emissions ***due to nitrate leaching*** correspond to 0.0075 kg N_2O-N per kg of N leaching.

The emissions of NO_x-N are calculated as 0.1* direct N_2O-N, based on Nemecek and Kägi (2007).

The N_2-N emissions are based on the estimates from SimDen (Vinther, 2004). For soil type JB3 the N_2-N:N_2O-N ratio is 3:1 and for soil type JB6 the N_2-N:N_2O-N ratio is 6:1.

G.7.5 Calculation of liquid fraction fertilizer value

The calculation of the liquid fraction fertilizer value is presented and detailed in section G.28.

G.7.6 Nitrate leaching

In order to calculate N leaching values, the same simplifying assumption as in Annex C is used: the liquid fraction, once the respective ammonia losses have been subtracted, can be modeled as: a given proportion of slurry + a given amount of mineral N. The present liquid fraction has a higher content of N relative to C, as compared to the original reference slurry. This is because the mechanical separation transfers relatively more C to the fibre fraction than N. As the amount of organic matter is one of the key properties for its effect on the N partitioning, the amount of C relative to N in the cow slurry from the reference scenario is used. The N values are taken after ammonia volatilization. The C:N proportion is 45.2 [kg C] / (5.79-0.02-0.73) [kg N] = 8.97 for the cow slurry and 13.44 [kg C] / (4.07-0.01-0.50) [kg N] = 3.78 for the liquid fraction. The “virtual” proportion of N assumed to affect the soil and plants as raw slurry is therefore 3.78 /8.97 = 0.42, and the virtual proportion of N assumed to affect the soil and plants as mineral N is accordingly 0.58. The tables A.14 and A.16 of Annex A are therefore the basis for the calculation of N leaching, after correcting for their respective ammonia volatilization.

G.7.7 Phosphorus leaching

For P leaching, the same assumptions as those used in Annex A were used, i.e., 10% of the P applied to field has the possibility of leaching and 6% of this actually reach the aquatic recipients, based on Hauschild and Potting (2005).

G.7.8 Cu and Zn fate

As in Annex A, it is considered that the entirety of the Cu and Zn applied will leach through the water compartment.

G.7.9 Life cycle data for field application of liquid fraction

Table G.18 presents the life cycle data for the application of ex-storage liquid fraction on the field. The results of the reference case (Annex A) are also presented for comparison purposes. However, in order to be comparable, both results must be related to the functional unit, i.e. 1000 kg slurry ex-animal.

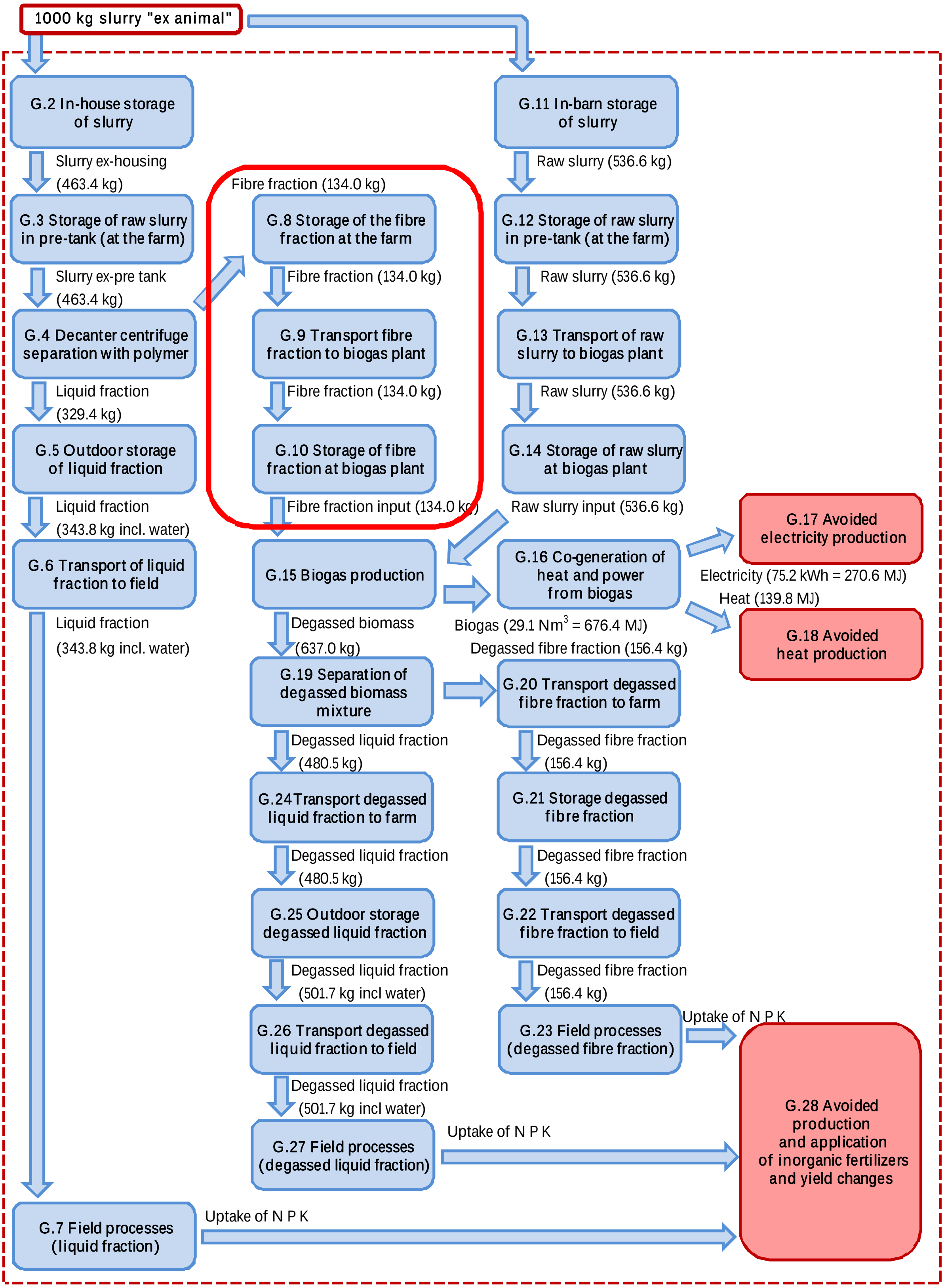
Table G.18.
Life cycle data for the field processes related with the application of liquid fraction. All data per 1000 kg of “liquid fraction ex-storage”. Dairy cow slurry.

	Dairy cow slurry (Annex A)	Liquid fraction after storage (Annex G)	Comments
Input			
Slurry/ liquid fraction “ex-storage”	1000 kg	1000 kg	Slurry / liquid fraction from the outdoor storage.
Output			
Slurry on field, fertiliser value	Fertiliser replacement value: 4.21 kg N 0.98 kg P 5.65 kg K	Fertiliser replacement value, N, P and K: see section G.28.	
Energy consumption			
Diesel for slurry	0.4 litres of diesel	0.4 litres of diesel	See text.
Emissions to air			
Carbon dioxide (CO_2) Soil JB3 Soil JB6	 126.4 (154.5) kg 124.2 (153.8) kg	 30.3 (43.9) kg 29.7 (43.7) kg	Modelled by C-TOOL (Gyldenkærne et al, 2007). 10 year value shown, 100 years value in parenthesis.
Methane (CH_4)	Negligible	Negligible	The CH_4 emission on the field are assumed to be negligible, as the formation of CH_4 requires anoxic environment (the field is aerobic) (Sherlock et al., 2002).
Ammonia (NH_3-N) during application	0.02 kg	0.0118 kg	NH3 emissions during application: 0.5% of NH4+-N “ex-storage”, the NH4+-N “ex-storage” being evaluated as 58 % of total N. Calculation based on Hansen et al. (2008), see text. 4.07 kg N * 58% * 0.5% = 0.0118 kg NH_3-N
Ammonia (NH_3-N) in period after application	0.73 kg	0.500 kg	Correspond to 50 % of the emissions calculated as in Annex A. In Annex A, it is considered that there is a loss of 0.217 kg NH_3-N per kg of NH4-N (including losses of NH_3-N during application). NH4+-N is here evaluated as 58 % of total N. 50% * [0.217 kg NH_3-N/kg TAN * 58% * 4.07 kg N-0.0118 kg NH_3-N during application] = 0.500 kg NH_3-N.
Direct emissions of Nitrous oxide (N_2O-N)	0.06 kg [0.018-0.18]	0.0407 kg [0.012-0.12]	0.01 [0.003 - 0.03] kg N_2O-N per kg N “ex-storage” for application of animal wastes to soil, based on IPPC (IPCC, 2006: table 11.1). A sensitivity analysis has been made for N_2O emissions corresponding to 0.4% of applied N (see text).
Indirect emissions of Nitrous oxide (N_2O-N) Soil JB3 Soil JB6	0.006 kg 0.016 kg (0.019 kg) 0.0125 kg (0.015 kg)	0.00516 kg 0.012 kg (0.014 kg) 0.009 kg (0.011 kg)	Indirect emissions due to emissions of ammonia and NO_X: 0.01 kg N_2O–N per kg (NH_3–N + NO_X–N) volatilised (IPCC, 2006). Indirect emissions due to nitrate leaching: 0.0075 kg N_2O–N per kg N leaching (IPCC, 2006). 10 year value shown, 100 years value in parenthesis.
Nitrogen oxides (NO_x-N)	0.006 kg	0.00407 kg	NO_X–N = 0.1 * direct N_2O-N according to Nemecek and Kägi (2007)

Table G.18. (Continuation)
Life cycle data for the field processes related with the application of liquid fraction. All data per 1000 kg of "liquid fraction ex-storage". Dairy cow slurry.

	Dairy cow slurry (Annex A)	Liquid fraction after storage (Annex G)	Comments
Emissions to air			
Nitrogen (N_2-N) Soil JB3 Soil JB6	 0.18 kg 0.36 kg	 0.1221 kg 0.2442 kg	Estimated from the SimDen model ratios between N_2-N and N_2O-N (see text): 3:1 for soil JB3 and 6:1 for soil JB6.
Discharges to soil			
Nitrate leaching Soil JB3 Soil JB6	 2.16 (2.59) kg N 1.67 (2.04) kg N	 1.62 (1.87) kg N 1.26 (1.47) kg N	See text
Phosphate leaching	0.098 kg P	0.0436 kg P	10 % of the P applied to field, see text.
Copper (Cu)	0.0116 kg	0.0148 kg	100 % of the Cu applied is assumed the leach
Zinc (Zn)	0.0224 kg	0.0281 kg	100 % of the Zn applied is assumed the leach

Processes G.8 to G.10: Handling the fibre fraction from the farm to the biogas plant before biogas is produced



G. 8 Storage of the fibre fraction at the farm

At the farm, the fibre fraction is stored in a covered concrete container (Rosager, 2009). The storage duration varies between 1 and 3 days, the maximum being approximately 7 days (Jensen, 2009).

It is here important to highlight that the fibre fraction is stored in a covered structure. In fact, covering has a major mitigation impact on composting activity and on production and emission of greenhouse gases and NH_3, as further discussed in section G.21.

The emissions occurring during the storage of the fibre fraction are highly variable and are dependent upon various parameters such as the chemical composition and structure of the fibre fraction, the temperature and the storage time (Hansen, 2009; Dinuccio et al., 2008). The porous structure of the fibrous fraction causes a potential for a higher N loss during the storage and handling phases, especially as ammonia, as compared to raw manure (Petersen and Sørensen, 2008). However, Jørgensen and Jensen (2009) found no major differences in the proportion of NH_4-N of total N when they compared samples of fibre fractions that underwent 2 to 8 weeks storage to fibre fractions samples that were taken directly from the separator. This was true for 6 of their 7 samples of stored fibre fractions. Their stored fibre fractions samples were issued from both close and open storage. One of the hypotheses formulated by the authors to explain the non-significantly different proportions of NH_4-N from stored and fresh fibre fractions is that the storage period was not long enough to influence the apparent composition of N in the solids.

Based on these findings as well as on information from biogas producers (Rosager, 2009), the emissions occurring during the temporal storage of the fibre fraction at the farm are considered as negligible. Because it is considered that no losses occurs during this 1 to 3 days storage, the fibre fraction after the storage has the same composition as at the outlet of the separator (as presented in table G.8).

It is acknowledged that this is an important assumption impacting the whole mass balances for all subsequent process. As such, it is not a suitable to carry out a sensitivity analysis on this. Instead, the importance of this assumption is raised as a discussion point in the interpretation of the results.

The material consumption related to the storage facilities is as described in table G.19. This is based on the process “slurry store and processing” from the Ecoinvent database (Nemecek and Kägi, 2007, p.182), which is for a covered concrete tank with 300 m^3 capacity. It is estimated that an annual amount of 15 000 m^3 of fibre fraction will be handled per year.

Table G.19
Material consumption data related to the infrastructures needed for the storage of the fibre fraction.

Materials	Amount of material	Estimated life time	Amount of fibre fraction per year [m^3 per year]	Amount of fibre fraction in a life time [a] [m^3 in a life time]	Weight [per 1000 kg fibre fraction]
Storage facility					
Reinforcing steel	6 780 kg	40 years	15000 m^3 / y	600000 m^3 (3.6*10^8 kg)	18.8 g
Concrete	110 m^3	40 years	15000 m^3 / y	600000 m^3 (3.6*10^8 kg)	0.000306 m^3

a)The density of the fibre fraction was assumed to be 600 kg/m^3, based on Brauer (2006).

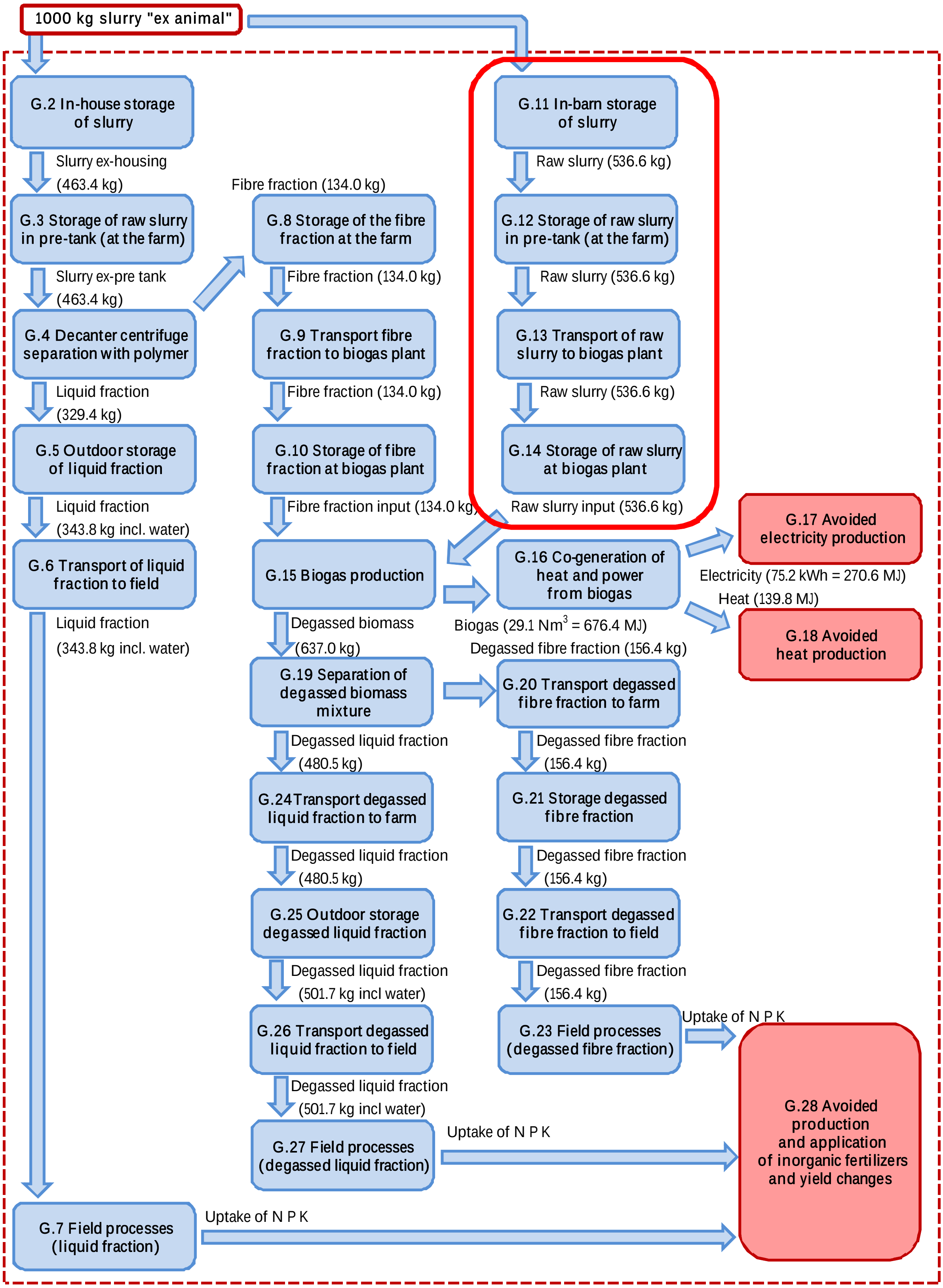
G.9 Transport of fibre fraction to biogas plant

The calculations for the transport of the fibre fraction to the biogas plant will be made for a transportation distance of 10.6 km (based on Laursen, 2009). The fibre fraction is transported by trucks. The transport is modelled by use of the Ecoinvent process “Transport, lorry >32t, EURO3” (Spielmann et al., 2007; table 5-124, p.96). As transport distance is not anticipated to have a considerable influence on the environmental impacts in the overall scenario (based on the results obtained by Wesnæs et al., 2009), no sensitivity analysis was carried out for a greater transport distance.

G.10 Storage of the fibre fraction at the biogas plant

Once at the biogas plant, the fibre fraction is stored for a very short period – from a few days to maximum a week (Rosager, 2009). As for process G.8, this means that the emissions occurring during the temporal storage of the fibre fraction at the biogas plant are considered as negligible. The equipment and materials for this storage are included in the material list for the biogas plant in table G.24.

Processes G.11 to G.14: Handling the raw slurry input for biogas: from in-house storage to storage at the biogas plant.



G.11 In-house storage of raw slurry

The assumptions and Life Cycle Inventory data for the storage of slurry in the housing units are the same as for the reference scenario (section A.2, Annex A), and thereby the same as described in section G.2.

G.12 Storage of raw slurry in pre-tank

This process is identical to the process described in section G.3. Therefore, the same life cycle data applies here.

G.13 Transport of raw slurry to biogas plant

For the transport of untreated slurry to the biogas plant, a distance of 5 km is assumed between the farm and the biogas plant. This distance is based on the fact that farmers transporting raw slurry are located nearby the biogas plant, so it pays-off to transport raw slurry rather than separated slurry.

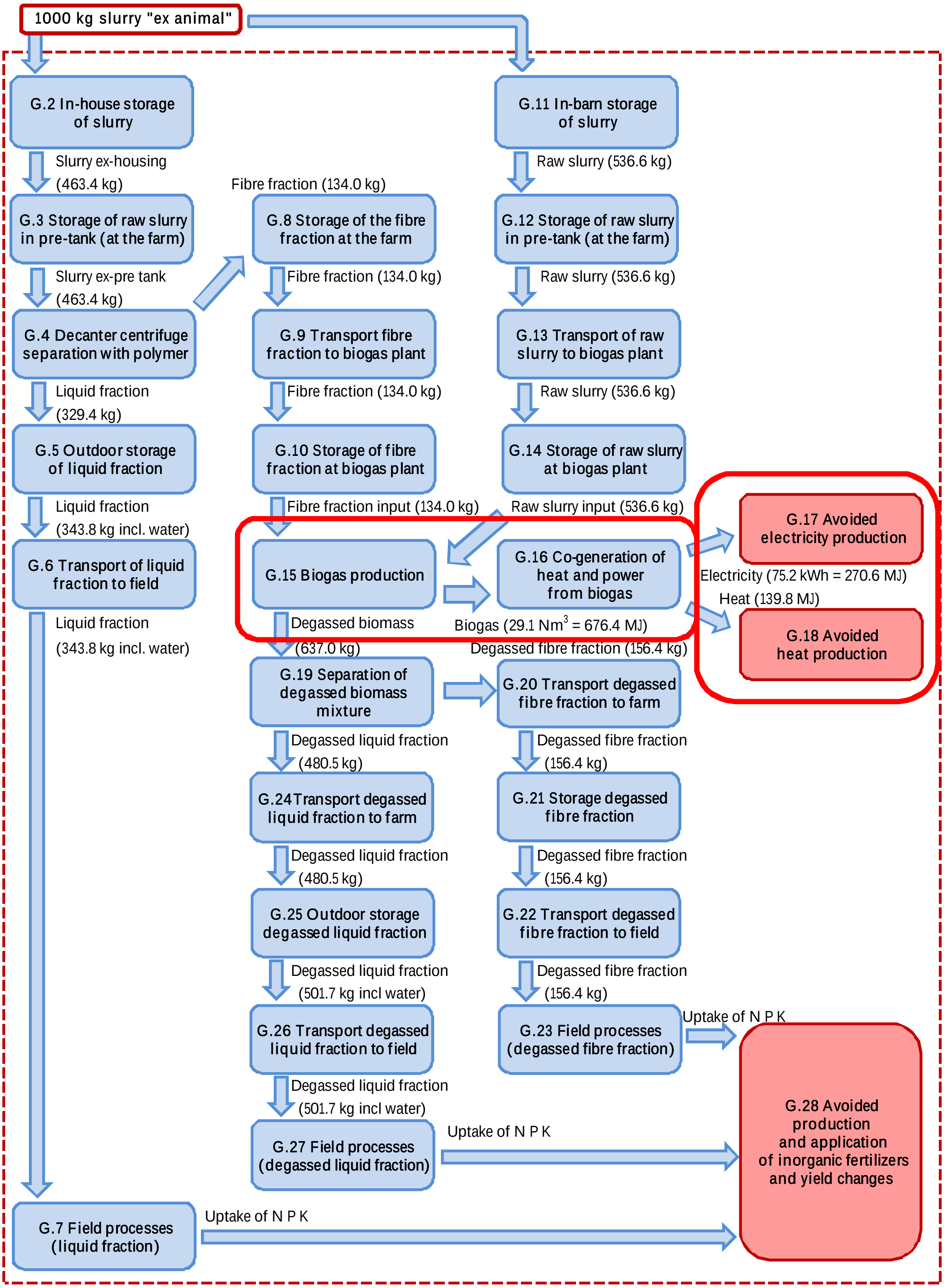
As transport distance is not anticipated to have a considerable influence on the environmental impacts in the overall scenario (based on the results obtained by Wesnæs et al., 2009), no sensitivity analysis was carried out for a greater transport distance.

The slurry is transported by trucks. The transport is modelled by use of the Ecoinvent process “Transport, lorry >32t, EURO3” (Spielmann et al., 2007; table 5-124, p.96).

G.14 Storage of the raw slurry at the biogas plant

The raw slurry is stored at the biogas plant for a rather short time, since the storage capacity available at the biogas plant is limited. Therefore, no emissions were considered for this temporal stage. The composition of the raw slurry is therefore the same as the ex pre-tank slurry (see table G.3).

Processes G.15 to G.18: Biogas production, co-generation of heat and power and avoided heat and electricity production



G.15. Biogas production

G.15.1 Biogas principles

Biogas production occurs in anaerobic environments where organic matter is degraded by biological activity. The result of the anaerobic digestion is the release of gasses and nutrients. The produced gas is rich in methane (50-70 %) and carbon dioxide (50-30%) and with smaller amounts of other gasses such as hydrogen sulphide and nitrogen (N_2). The relative composition of the biogas mixture depends of the process conditions and the substrate digested (Nielsen, 2009), but is however mostly constituted of CH_4 and CO_2. Biogas is considered as a valuable energy source because of CH_4, since it is because of this gas that biogas is combustible (Nielsen, 2009).

According to Nielsen (2009), when pig manure is anaerobically digested at 50°C, there is between 50 and 70 % of CH_4 and between 30 and 50 % of CO_2 in the biogas. In this project, it is assumed that the biogas produced is constituted of 65 % CH_4 and 35% CO_2. This is in accordance with the biogas composition reported in the recent literature. In fact, Møller et al. (2007a) measured an average of 65 % CH_4 in a digester where a total of 60 % of fibre fraction was gradually incorporated to the biomass mixture (consisting of liquid manure from fattening pigs mixed with the fibre fraction). The biogas composition found in the Ecoinvent database (Jungbluth et al., 2007, p.180) consists of 67% CH_4 and 32.05% CO_2, the remaining 0.95 % being a mixture of N_2, O_2 and H_2S.

The biogas density[8] is 1.158 kg/Nm^3. Based on a heat value for methane of 9.94 kWh/Nm^3 CH_4, the heat value of the biogas is 6.46 kWh/Nm^3 biogas[9]. The lower heat value of the biogas in the Ecoinvent database is 24.043 MJ/Nm^3 (for the biogas used in the biogas engine, Jungbluth et al., 2007, page 180) which is in the same magnitude as the heat value in this study, namely 23.26 MJ/Nm^3 (i.e. 6.46 kWh/Nm^3 biogas * 3.6 MJ/kWh).

Biogas is not the only output of the process, as digested slurry is also produced. This digested slurry is recognized to have slightly different properties as compared to undigested slurry as a result of the digestion process. In fact, during the anaerobic degradation nutrients bound to the organic matter are released and thereby made more accessible for uptake by plants.

The biogas plant considered in this project consists of bioreactors for the biogas production, of receiving facilities and storage tanks for raw and degassed (digested) biomass, respectively, and of a co-generation unit allowing to produce heat and electricity from the biogas. In the current context, the biogas plant used for the calculations is based on a two-step digestion with an annual treatment capacity of 100 000 m^3 of biomass. Both steps are continuously operated and fully mixed in overflow tanks with a

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[8] 65% CH_4 with a density of 0.717 kg/Nm^3 plus 35% CO_2 with a density of 1.977 kg/Nm^3 gives a total density of (0.65*0.717 + 0.35*1.977) kg/Nm^3 = 1.158 kg/Nm^3.

[9] The heat value is calculated as: 9.94 kWh/Nm^3 CH_4 x 65 % CH_4 = 6.46 kWh/Nm^3 biogas.

hydraulic retention time defined by the ratio between the digester volume and the daily biomass input volume.

The first step typically yields 80-90 % of the final biogas yield and is a carefully controlled process in terms of temperature, retention time and loading. The second step is a post-digestion tank often without temperature control and with a relatively low loading. The biogas plant is an air-tight system and therefore principally without any uncontrolled gaseous emissions.

The rate of biogas production depends on the nature of the biomass input (e.g. VS-content, degradability and nitrogen content) and the process conditions applied. Process temperature is highly determining for maximum gas production rate. Industrial biogas systems are typically operated at either mesophilic temperatures (around 37 °C) or thermophilic temperatures (around 52 °C). The potentially higher gas production rate in a thermophilic process can be counteracted by a temperature dependent ammonia inhibition. As the biogas scenarios investigated in the present LCA comprises a biomass with high nitrogen loading, the biogas model system will be mesophilic thereby eliminating nitrogen loading as a limiting factor when biomass mixtures are calculated.

In order to determine the final output in terms of energy, the efficiency of the co-generation unit must be known for both heat and electricity. This is further detailed in section G.16.

Table G.20 summarizes the different parameters used in this project as regarding biogas production.

Table G.20
Summary of the main parameters characterizing the biogas process

Parameter	Value
Biogas Composition	
CH_4	65 %
CO_2	35 %
Biogas density	1.158 kg/Nm^3 biogas
Engine efficiency [a)]	
Heat	46 %
electricity	40 %
Heat value	6.46 kWh/Nm^3 biogas (23.26MJ/Nm^3 biogas)

[a] See section G.16.

G.15.2 Biomass mixture entering the biogas plant

The biomass mixture input in the anaerobic digester is constituted of raw slurry (the composition of which is shown in table G.3) and fibre fraction (the composition of which is shown in table G.8). According to the composition and the degradability of both fractions, the amount of both fractions in the mixture is determined in order to obtain a biomass mixture that has a DM of approximately 10% during the digestion ***in the reactor,*** in order to obtain realistic production conditions (Jensen, 2009).

According to calculations provided by Xergi (Jensen, 2009), the 1000 kg mixture of the biomass entering the biogas plant consists of:

- 800.20 kg raw slurry (ex pre-tank)

- 199.80 kg fibre fraction

The mixture composition and mass balances is shown in table G.21 below.

Table G.21.
Mass balances for the biomass entering the biogas plant, i.e. a combination of fibre fraction and raw cow slurry (slurry from **dairy cows**).

			Mass balances			
	Composition of the raw slurry $^{a)}$ [kg per 1000 kg slurry]	Composition of fibre fraction $^{b)}$ [kg per 1000 kg fibre fraction]	Amount in raw slurry [kg]	Amount in fibre fraction [kg]	Sum of mass [kg]	Composition of biomass entering the biogas plant $^{c)}$ [kg per 1000 kg biomass]
Total mass	1000 kg	1000 kg	800.20 kg	199.80 kg	1000 kg	1000 kg
Dry matter (DM)	113.2 kg	310.0 kg	800.20 /1000 * 113.2 kg = 90.58 kg	199.80/1000 * 310.0 kg =61.94 kg	152.52 kg	152.52 kg
Total-N	6.34 kg	10.96 kg	800.20 /1000 * 6.34 kg = 5.07 kg	199.80/1000 * 10.96 kg = 2.19 kg	7.26 kg	7.26 kg
Total-P	1.03 kg	2.44 kg	800.20 /1000 * 1.03 kg = 0.824 kg	199.80/1000 * 2.44 kg = 0.488 kg	1.312 kg	1.312 kg
Potassium (K)	5.9 kg	4.08 kg	800.20 /1000 * 5.9 kg = 4.72 kg	199.80 /1000 * 4.08 kg = 0.815 kg	5.535 kg	5.535 kg
Carbon (C)	49.7 kg	136.11 kg	800.20 /1000 * 49.7 kg = 39.77 kg	199.80/1000 * 136.11 kg = 27.195 kg	66.965 kg	66.965 kg
Copper (Cu)	0.0121 kg	0.0038 kg	800.20 /1000 * 0.0121 kg = 0.0097 kg	199.80/1000 * 0.0038 kg = 0.0008 kg	0.0105 kg	0.0105 kg
Zinc (Zn)	0.0234 kg	0.0090 kg	800.20 /1000 * 0.0234 kg = 0.0187 kg	199.80/1000 * 0.0090 kg = 0.0018 kg	0.0205 kg	0.0205 kg

a) Same as in table G.3 (which is from ex-housing slurry in Annex A)
b) Same as in table G.8
c) Composition of biomass mixture of slurry and fibre fraction entering the biogas plant, i.e. the biomass input into the digester

In this project, the functional unit is “Management of 1000 kg slurry ex-animal”. The biogas production therefore has to be related to the functional unit by the use of mass balances, i.e. the values expressed per 1000 kg of biomass mixture must be converted in order to be expressed per 1000 kg of slurry ex-animal. To do this, the amount of biomass mixture (800.20 kg raw slurry plus 199.80 kg fibre fraction) used per 1000 kg of slurry ex-animal must be calculated. This calculation can be done in 6 steps:

- ***Step 1: Defining the total amount of “ex-animal” slurry involved – contribution from the raw slurry input***
  The 800.20 kg raw slurry entering the biogas plant is “ex pre-tank” corresponds to the same amount of “ex-animal” slurry, since it is assumed that no water was added during the storage in the pre-tank. Therefore, the amount of raw slurry ex-animal from this input is 800.20 kg.

- ***Step 2: Defining the total amount of "ex-animal" slurry involved – contribution from the fibre fraction input***
  The 199.80 kg of fibre fraction origins from 690.90 kg slurry ex-housing as 289.19 kg of fibre fraction is produced from 1000 kg of ex pre-tank (and hereby the same as ex-housing) cow slurry that is mechanically separated (table G.8)[10]. The mass of slurry ex-housing is considered to be the same as the slurry ex-animal (see table A.4 and A.9, Annex A). This means that 690.90 kg of slurry ex-animal were necessary to produce the 199.80 kg of fibre fraction.
- ***Step 3: Defining the total amount of "ex-animal" slurry involved – sum of the two biomasses input***
  It means that a biomass mixture of 800.20 kg raw slurry + 199.80 kg fibre fraction origins from: 800.20 kg + 690.90 kg = 1491.10 kg cow slurry ex-animal.
- ***Step 4: Relating the 800.20 kg of raw slurry input to the functional unit (1000 kg slurry ex-animal)***
  As the functional unit in this study is 1000 kg slurry ex-animal, the amount of "raw slurry for biogas mixture" is: 800.20 kg *1000 kg / 1491.10 kg = 536.65 kg raw slurry (ex pre-tank) per 1000 kg slurry ex-animal (and 536.65 kg raw slurry ex pre-tank corresponds to approximately 536.65 kg slurry ex-animal, as there is no water addition during the in-house storage).
- ***Step 5: Relating the 199.80 kg of fibre fraction input to the functional unit (1000 kg slurry ex-animal)***
  The amount of fibre fraction needed for the biogas mixture is: 199.80 kg *1000 kg / 1491.10 kg = 134.00 kg fibre fraction per 1000 kg slurry ex-animal (and 134.00 kg fibre fraction corresponds to approximately 463.36 kg cow slurry ex-animal[11]).
- ***Step 6: Total biomass input needed per functional unit***
  The biomass needed for the process is then 536.65 kg cow slurry (ex pre-tank) + 134.00 kg fibre fraction = 670.65 kg "biomass mixture" entering the biogas plant per 1000 kg of slurry "ex-animal".

G.15.3 Energy consumption during biogas production and heat value of the biogas produced

The amount of biogas produced is calculated assuming that the amount of VS corresponds to 80 % of DM. The following specific methane yields in Nm^3 per ton VS were assumed: cow slurry 231 Nm^3 per ton (210 Nm^3 per ton from primary digester + 10 % extra from secondary step); fibre fraction 231 Nm^3 per ton (210 Nm^3 per ton from primary digester + 10 % extra from secondary step). Slurry and fibre fraction methane yield are based on Møller (2007). The fibre fraction data used are those referred to as "solids flocculated with polymer" by Møller (2007). Also, it must be remembered that it was assumed that the biogas is constituted of 65 % CH_4 and 35 % CO_2 (table G.20).

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[10] 199.8 kg fibre fraction * (1000 kg slurry ex pre-tank/289.19 kg fibre fraction) * (1000 kg slurry ex-animal/1000 kg slurry ex pre-tank) = 690.90 kg slurry ex-animal.

[11] 134.00 kg fibre fraction * (1000 kg slurry ex pre-tank/289.19 kg fibre fraction) * (1000 kg slurry ex-animal/1000 kg slurry ex pre-tank) = 463.36 kg slurry ex-animal.

Using these figures, it means that a total of 43.36 Nm^3 biogas [12] per 1000 kg of "biomass mixture" is produced. The biogas density being 1.158 kg/Nm^3, a mass of 50.2 kg of biogas per 1000 kg of "biomass mixture" is therefore produced. The heat value of the biogas corresponds to 1008 MJ per 1000 kg biomass mixture"[13].

During the process, both heat and electricity are consumed. The electricity consumed for the production of biogas corresponds to the electricity used for the process plant (pumping, stirring etc.). This electricity consumption depends on the amount of biomass handled. The electricity consumed for producing the biogas is estimated as 5% of the net energy production (Jensen, 2009). This estimate is based on measurements. The electricity therefore consumed for producing the biogas corresponds to 5.60 kWh per 1000 kg "biomass mixture"[14]. This means a consumption of 0.129 kWh per Nm^3 biogas (5.60 kWh/1000 kg "biomass mixture" * 1000 kg "biomass mixture"/43.36 Nm^3 biogas). The magnitude of this value is in accordance with the values found in the literature. Jungbluth et al. (2007) reports a value of 0.132 kWh per Nm^3 biogas corresponding to the average electricity consumption for 14 Swiss biogas plants. Nielsen (2002) estimates that the internal electricity used corresponds to 0.09 kWh of electricity per m^3 of biogas produced. The value of 0.129 kWh per Nm^3 biogas used in this project therefore seems to correspond to the middle of the range of reported values. In some cases, however, the electricity consumption corresponds to 10% of the electricity produced (Jensen, 2009). Yet, this is not anticipated to be a major influence to the environmental impacts of the overall scenarios, so no sensitivity analysis was carried out for this. Instead, it is taken as a discussion point in the interpretation of the results.

The heat consumption for the process is calculated based on heating the fibre fraction and liquid from 8°C to the process temperature of 37°C (a temperature difference of 29°C), corresponding to 116.49 MJ per 1000 kg "biomass mixture" [15].The plant is insulated in order to reduce heat loss. Yet,

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[12] From cattle slurry: 800.20 kg slurry* 113.20 kg DM/ 1000 kg slurry * 0.8 kg VS per kg DM * 231 Nm^3 CH_4 per ton VS / 0.65 Nm^3 CH_4 per Nm^3 biogas * ton/1000 kg = 25.75 Nm^3 biogas.
From fibre fraction: 199.80 kg fibre fraction * 310.0 kg DM/1000 kg fibre fraction * 0.8 kg VS per kg DM * 231.00 Nm^3 CH_4 per ton VS / 0.65 Nm^3 CH_4 per Nm^3 biogas * ton/1000 kg = 17.61 Nm^3 biogas.
Total biogas produced per 1000 kg of "biomass mixture": 43.36 Nm^3 biogas (25.75 Nm^3 from slurry + 17.61 Nm^3 from fibre fraction).

[13] This is calculated using the heat value and the total biogas produced: 6.46 kWh/Nm^3 biogas (see table G.20) * 43.36 Nm^3 biogas/1000 kg "biomass mixture" * 3.6 MJ/kWh = 1008 MJ/1000 kg "biomass mixture".

[14] Estimated internal consumption of electricity in kWh per 1000 kg biomass mixture : 43.36 Nm^3 biogas/1000 kg biomass mixture x 6.46 kWh/Nm^3 biogas x 40 % engine power efficiency x 5 % internal consumption = 5.60 kWh per 1000 kg biomass mixture.

[15] It is assumed that the average temperature for the biomass is 8 °C when entering the process and that it is heated to 37°C (the process temperature). Specific heat is calculated based on the content of DM and water (calculated as 1-DM), assuming that the specific heat for DM corresponds to 3.00 kJ/kg°C and to 4.20 kJ/kg°C for water. As the DM for biomass mixture is 152.52 kg/1000 kg biomass mixture (table

some plants are equipped with heat exchangers in order to reduce the temperature difference to 15-20 °C (Rosager, 2009). The influence of this in the overall system is anticipated to be rather small and is raised as a discussion point in the interpretation of the results.

In summary, the energy consumption during the production of biogas consists of:

- 5.60 kWh of electricity per 1000 kg "biomass mixture"
- 116.49 MJ of heat per 1000 kg "biomass mixture".

G.15.4 Emissions of CH_4 and CO_2

As the biogas plant is constructed tight in order to reduce losses of biogas, the emissions to air during the digestion are assumed to be rather small.

Jungbluth et al. (2007, page 206) made a review of several references of methane emissions from agricultural biogas plants and found a range of the methane emissions of 1-4% of the produced methane for biogas plants with covered stocks. These authors however used a methane emission of 1% of the produced methane. Similarly, Börjesson and Berglund (2007) assumed that the uncontrolled losses of methane from the production of biogas correspond to 1 % of the biogas produced when the biogas is used for heat or combined heat and power. Börjesson and Berglund (2006) mention that due to the difficulties in measuring and quantifying net losses of methane from biogas production, such data are uncertain and limited. They also reports that these losses were typically assumed to 2 to 3 % in previous life cycle assessments. Sommer et al. (2001) estimated that 3% of the produced methane is lost to the environment due to leakages and non-combusted methane in the biogas engines. In this project, the estimate used by Jungbluth et al. (2007) as well as Börjesson and Berglund (2007), i.e. 1 % of the produced methane, will be used. This gives a CH_4 emission to air of 0.2025 kg (see calculations in table G.22).

For the emissions of CO_2, Jungbluth et al. (2007) used an emission of 1 % of the produced CO_2 in the biogas. In this project, the calculated ratio between emissions of CO_2 and CH_4 in anaerobic conditions will be used, i.e. 1.67 kg CO_2 per kg CH_4 (see section G.5.5). This gives a CO_2 emission of 0.338 kg/1000 kg biomass mixture. This corresponds to 1.1 % of the CO_2 produced in the biogas[16], which is in the same magnitude as the 1% estimate of Jungbluth et al. (2007).

G.21), it involves that the water content is 1000kg – 152.52 kg = 847.48 kg/1000 kg biomass mixture. The heat consumption for heating the biomass mixture from 8°C to 37°C is thus :
For DM: 152.52 kg DM/1000 kg biomass mixture * 3.00 kJ/kg DM*°C * (37-8) °C = 13 269.24 kJ/1000 kg biomass mixture;
For water : 847.48 kg water/1000 kg biomass mixture * 4.20 kJ/kg DM*°C * (37-8) °C = 103 223.06 kJ/1000 kg biomass mixture;
Total : (13 269.24 + 103 223.06) kJ/1000 kg biomass mixture * MJ/1000 kJ = 116.49 MJ/1000 kg biomass mixture.

[16] CO_2 produced in the biogas: 43.36 Nm^3 biogas * 35% CO_2 * 1.977 kg CO_2/Nm^3 CO_2 = 30 kg CO_2. The CO_2 emissions of 0.338 kg estimated in this project correspond to: 0.338 kg/30 kg * 100% = 1.1% of the CO_2 produced in the biogas.

G.15.5 Emissions of NH_3 and N_2O

The emissions of NH_3 and N_2O from the biogas plant are assumed to be insignificant. This is based on recent publications (e.g. Marcato et al., 2008; Massé et al., 2007) where measurements showed that there are no significant losses of N during the anaerobic digestion (of pig slurry).

G.15.6 Life cycle data and mass balances for anaerobic digestion process

In this scenario, the biogas is not upgraded (which is necessary if it is going to be used as fuel for transport). The biogas is used for co-production of electricity and heat. Table G.22 presents the life cycle data for the anaerobic digestion process.

Table G.22.
Life cycle data for the anaerobic digestion process. Data per 1000 kg biomass mixture into the biogas plant.

	Biomass mixture	Comments
Input		
Biomass mixture	1000 kg	All emissions are calculated relatively to 1000 kg "biomass mixture" (i.e. 80.02% raw slurry and 19.98% fibre fraction)
Output		
Biogas (65 % CH_4 and 35 % CO_2)	50.2 kg i.e. 43.36 Nm^3	Density 1.158 kg/Nm^3, see text.
Degassed slurry	949.8 kg	Gas output is dried. No water loss. Therefore, the only loss is the mass of the biogas : 1000 kg – 50.2 kg= 918.8 kg
Energy consumption		
Electricity	5.60 kWh	Estimated own consumption of electricity: 5 % of net production, engine efficiency of 40 % (see text). Electricity from the grid.
Heat	116.5 MJ	Heating the biomass from 8°C to 37°C, see text. Heat from the co-generation unit (see section G.16).
Emissions to air		
Carbon dioxide (CO_2)	0.338 kg	1.67 kg CO_2 per kg CH_4
Methane (CH_4)	0.2025 kg	1% of the methane content of the biogas is assumed to be emitted to the environment. 43.46 Nm^3 biogas * 65% CH4 * 0.717 kg/Nm^3 * 1% = 0.2025 kg CH4.
Ammonia (NH_3-N)		Assumed to be insignificant, see text
Nitrous oxide (N_2O-N)		Assumed to be insignificant, see text
Nitrogen oxides (NO_X)		Assumed to be insignificant, see text
Nitrogen monoxide(NO)		Assumed to be insignificant, see text
Nitrogen(N_2)		Assumed to be insignificant, see text
Hydrogen sulphide (H_2S)		Assumed to be insignificant compared to the emissions from the following co-production of electricity and heat.
Odour		No data
Emissions to water		
		No emissions to water
Emissions to soil		
		No emissions to soil

The composition of the degassed slurry after biogas production is shown in table G.23. It is based on mass balances from data presented in table G.22 for the total mass, the DM content and the total N.

It is acknowledged that some elements may remain in the reactor (e.g. as a precipitate). With a mixture consisting of pig slurry only, Massé et al. (2007)

measured statistically significant accumulation of: 25.5 ± 7.5 % of the initial P, 41.5 ± 14.8 % of the initial Cu and 67.7 ± 22.9 % of the initial S. These represent averages obtained in two cycles. For Zn, Ca and Mn, Massé et al. (2007) measured an average retention of 18.4 ± 17.7 %, 8.7 ± 9.8 % and 21.0 ± 21.9 % respectively, but this was statistically significant only for one cycle. Similarly, in an experiment where pig slurry was digested, Marcato et al. (2008) observed significant losses for P, Ca, Mg and Mn (36 %, 44 %, 32.5 % and 32 % of the respective elements were lacking in the output slurry as compared to the input slurry). Marcato et al. (2008) explained these losses by the accumulation of these elements in the form of a precipitate in the reactor, which they confirmed by scanning electron microscopy observations. As opposed to the results of Massé et al. (2007), there were no significant losses of S, Cu and Zn in the results of Marcato et al. (2008). However, both studies agree as regarding losses of P in the bioreactor, and the magnitude are comparable. Nevertheless, it was decided, based on interviews with managers and experts of Danish biogas plants (Karsten Buchhave, 2009; Jesper Andersen, 2009 and Henrik Laursen, 2009), to consider that no losses are involved through precipitation. Given the performances of the agitator systems found in the digesters nowadays in Denmark, it is reasonable to assume that no precipitates are formed in the digesters (Norddahl, 2009). Moreover, based on the interviews mentioned above, it is considered that no acid is added in the slurry in order to prevent the formation of such a precipitate. This situation is judged representative of the recently built Danish biogas plants as well as of those to be built in the future.

Table G.23.
Mass balances for the biogas mixture before and after the biogas plant

	Composition of Mixture of slurry and fibre fraction entering the biogas plant [kg per 1000 kg biomass mixture]	Mass balance: Change during biogas production [kg]	Mass balance: Amount after biogas production [kg]	Composition of Degassed biomass after biogas production [a] [kg per 1000 kg degassed biomass]
Total mass	1000 kg	- 50.2 kg [b]	949.8 kg	1000 kg
Dry matter (DM)	152.52 kg	- 50.2 kg [c]	102.32 kg	107.73 kg
Total-N	7.26 kg	No change	7.26 kg	7.64 kg
Total-P	1.312 kg	No change	1.312 kg	1.381 kg
Potassium (K)	5.535 kg	No change	5.535 kg	5.828 kg
Carbon (C)	66.965 kg	- 23.56 kg [d]	43.405 kg	45.699 kg
Copper (Cu)	0.0105 kg	No change	0.0105 kg	0.0111 kg
Zinc (Zn)	0.0205 kg	No change	0.0205 kg	0.0216 kg

a) All the data are the same as in the precedent column, but adjusted to be expressed per 1000 kg of degassed mixture, instead of per 918.8 kg of degassed mixture.
b) This loss corresponds to the biogas produced, expressed in mass terms.
c) No water loss and therefore change in dry matter is equal to change in total mass.
d) This corresponds to the losses in the biogas itself and the losses that occurred during the digestion process:
Losses in the biogas are calculated as the sum of CH_4-C and CO_2-C: (43.36 Nm^3 biogas * 65 % CH_4 * 0.717 kg CH_4/Nm^3) * (12.011 g/mol /16.04 g/mol) + (43.36 Nm^3 biogas * 35 % CO_2 * 1.977 kg CO_2/Nm^3) * (12.011 g/mol /44.01 g/mol) = 23.320 kg C
Losses from the digestion process are the aggregated losses as CO_2-C + CH_4-C: 0.338 kg CO_2 * (12.011 g/mol /44.01 g/mol) + 0.2025 kg CH_4 * (12.011 g/mol /16.04 g/mol) = 0.244 kg C
Total C loss : 23.320 kg C + 0.244 kg C = 23.56 kg C.

G.15.7 Material consumption for the anaerobic digestion plant

The materials for the anaerobic digestion plant are taken from the Ecoinvent process “Anaerobic digestion plant covered, agriculture” (Jungbluth et al., 2007, p. 197) with a capacity of 500 m^3 (biomass) and a life time of 20 years (table G.24). A typically Danish biogas plant has a treatment capacity of 100 000 m^3 biomass a year (Jensen, 2009). This includes the bioreactor only, i.e. the storage tanks and co-generation unit are not included. Electronics for operating the system are however included.

Table G.24.
Material consumption for an anaerobic digestion plant.

Materials	Weight of material in plant	Estimated life time	Amount of slurry per year [m^3 slurry per year]	Amount of slurry in a life time [m^3 slurry in a life time]	Weight [per 1000 kg slurry]
Anaerobic digestion Plant					
Concrete	120 m^3	20 years	100 000 m^3 / y	2 000 000 m^3	0.00006 m^3
Reinforcing steel	10800 kg	20 years	100 000 m^3 / y	2 000 000 m^3	5.4 g
Steel, chromium steel 18/8	1300 kg	20 years	100 000 m^3 / y	2 000 000 m^3	0.65 g
Glued laminated timber	80 m3	20 years	100 000 m^3 / y	2 000 000 m^3	0.00004 m^3
Cobber	250 kg	20 years	100 000 m^3 / y	2 000 000 m^3	0.125 g
Polystyrene, high impact	570 kg	20 years	100 000 m^3 / y	2 000 000 m^3	0.285 g
Polyethylene	170 kg	20 years	100 000 m^3 / y	2 000 000 m^3	0.085 g
Polyvinyleidenchloride	330 kg	20 years	100 000 m^3 / y	2 000 000 m^3	0.165 g
Synthetic rubber	1200 kg	20 years	100 000 m^3 / y	2 000 000 m^3	0.6 g
Electronics / PC [a)]	2 kg	5 years	100 000 m^3 / y	500 000 m^3	0.001 g

a)The computer and electronics for the operating system is not included in the Ecoinvent database. It is added in this study.

G.16 Co-generation of heat and power from biogas

The biogas produced is used for the production of electricity and heat. A biogas engine is used for this purpose. In order to estimate the net heat and electricity production, the engine efficiencies (for conversion of biogas to both heat and electricity) are needed. The efficiencies of the best available technology have been applied. According to the technical description of biogas engines from GE Energy (GE Energy, 2008), the efficiency for the electricity production is in the range of 36.7%-40.8% and the efficiency for heat production is in the range of 42.9%-48.9%, with a maximum total efficiency of 82.5-86%. Accordingly, the calculations have been carried out considering an electricity efficiency of 40% and a heat efficiency of 46%.

As detailed in section G.15.3, the system produces 43.36 Nm^3 biogas per 1000 kg of biomass mixture. As there are 670.65 kg biomass mixture per 1000 kg slurry ex-animal (see detailed calculation in section G.15.2), this corresponds to a production of 29.1 Nm^3 biogas per 1000 kg slurry ex-animal[17]. The net energy production after the co-generation unit is therefore

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[17] 670.65 kg biomass mixture (per 1000 kg slurry ex-animal) * 43.36 Nm^3 / 1000 kg biomass mixture = 29.1 Nm^3 biogas per 1000 kg slurry ex-animal.

311.36 MJ heat plus 75.2 kWh electricity (270.7 MJ) per 1000 kg slurry ex-animal[18].

As also detailed in section G.15.3, some of the produced heat is used to fulfil the heat demand of the biogas production. The amount of heat needed for this purpose is 116.49 MJ per 1000 kg mixture input, which corresponds to 78.1 MJ per 1000 kg slurry ex-animal[19]. The heat consumption by the biogas plant thus corresponds to 78.1 MJ/ 311.36 MJ = 25 % of the heat produced. The surplus heat for the system is 311.36 MJ – 78.1 MJ = 233.26 MJ for the total system.

Yet, not all of this surplus heat can actually be used. In fact, the amount of "usable" surplus heat from the biogas plant must reflect the fact that in Denmark, according to the seasonal variations, there are periods with a surplus of heat production, which means that the heat produced at the biogas plant cannot be used during these periods, as there is no demand for it.

In the framework of the Danish LCAfood project, Nielsen (2004) assumed that only 50 % of the net heat produced by farm scale biogas plants is actually used, the remaining 50 % being simply wasted.

In the case of this project (joint scale biogas plants), it was assumed that 60 % of the surplus heat produced at the biogas plant is used, the remaining 40 % being wasted. This is a rather rough assumption based on the averaged national monthly heat demand distribution.

Therefore, out of the 233.26 MJ per 1000 kg slurry ex-animal of net surplus heat, only 139.96 MJ (i.e. 233.26 MJ * 60%) are used to fulfil the heat demand. The wasted heat thus corresponds to 93.3 MJ.

The energy produced from the biogas can be summarized as:

- 75.2 kWh electricity (270.7 MJ) per 1000 kg slurry ex-animal, all used through the national electricity grid, low voltage electricity.
- 311.36 MJ heat per 1000 kg slurry ex-animal, of which:
    - 78.1 MJ per 1000 kg slurry ex-animal is used for fulfilling the heat demand of the biogas process itself;
    - 139.96 MJ per 1000 kg slurry ex-animal is used to fulfil national heat demand;
    - 93.3 MJ per 1000 kg slurry ex-animal is wasted.

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[18] Heat produced: 29.1 Nm^3 biogas (per 1000 kg slurry ex-animal) * 23.26 MJ/ Nm^3 biogas (heat value of the biogas, see table G.20) * 0.46 (engine efficiency for heat) = 311.36 MJ heat per 1000 kg slurry ex-animal.
Electricity produced: 29.1 Nm^3 biogas (per 1000 kg slurry ex-animal) * 23.26 MJ/ Nm^3 biogas (heat value) * 0.40 (engine efficiency for electricity) = 270.7 MJ electricity per 1000 kg slurry ex-animal. This corresponds to 270.7 MJ * kWh/3.6 MJ = 75.2 kWh electricity per 1000 kg slurry ex-animal.

[19] There is 670.65 kg biomass mixture per 1000 kg slurry ex-animal, see section G.15.2. The heat required for the process is 116.49 MJ per 1000 kg mixture (section G.15.3). The heat needed per functional unit corresponds to: 670.65 kg biomass mixture / 1000 kg slurry ex-animal * 116.49 MJ / 1000 kg biomass mixture = 78.1 MJ per 1000 kg slurry ex-animal.

The emissions from the biogas engine were estimated from recent data from the Danish National Environmental Research Institute (DMU, 2009) (plants in agriculture, combustion of biogas from stationary engines).

Table G.25 presents the life cycle data related to the co-generation of heat and power from the biogas engine.

Table G.25.
Life cycle data for the co-generation of heat and power from biogas. Data per 1 MJ energy input.

	Per MJ input	Comments
Input		
Biogas	0.043 Nm^3 (1 MJ)	Amount of biogas corresponding to an energy content of 1 MJ input.[1 MJ/23.26 MJ/Nm^3] = 0.043 Nm^3.
Co-generation unit	5.0 E-9 p	Engine, generator, electric parts etc. divided by lifetime (Data from Jungbluth et al., 2007, table 13.20 of page 259)
Lubricating oil	3.0 E-5 kg	Production and disposal of used mineral oil included (Data from Jungbluth et al., 2007, table 13.20 of page 259)
Output		
Heat	0.46 MJ	The efficiency of the heat production is 46% (see table G.20)
Electricity	0.40 MJ	The electricity efficiency is 40% (see table G.20)
Emissions to air		
Carbon dioxide (CO_2)	8.36 E-2 kg	DMU (2009)
Carbon monoxide (CO)	2.73 E-4 kg	DMU (2009)
Methane (CH_4)	3.23 E-4 kg	DMU (2009)
Non-methane volatile organic compounds (NMVOC)	1.40 E-5 kg	DMU (2009)
Ammonia (NH_3-N)		No data
Nitrous oxide (N_2O)	1.59 E-7 kg	DMU (2009)
Nitrogen oxides (NO_X)	5.40 E-4 kg	DMU (2009)
Nitrogen monoxide(NO)		No data
Nitrogen(N_2)		No data
Particulates PM_{10} $PM_{2.5}$	 4.51 E-7 kg 2.06 E-7 kg	DMU (2009)
Hydrogen sulphide (H_2S)		No data
Sulphur dioxide (SO_2)	1.92 E-5 kg	DMU (2009)
Odour		No data
Emissions to water		
		No emissions to water
Emissions to soil		
		No emissions to soil

G.17 Avoided electricity production

The electricity that is replaced is the marginal electricity on the grid to which the plant is connected. As described in Annex A (section A.3.6), the modelling of marginal electricity in Denmark is based on Lund (2009), who considered detailed energy system analysis in order to determine a mix electricity marginal, considering that the marginal supplying technology differs every hour. Based on this, the Danish marginal electricity used in this project consists of 1% wind, 51% Power Plant (coal), 43% Power Plant (natural gas) and 5% electric boiler.

As 100 % coal or 100 % natural gas is generally the marginal electricity considered in life cycle assessments (Mathiesen et al., 2009), these have been used for the sensitivity analysis.

G.18 Avoided heat production

As for electricity, the heat avoided is the heat produced by the marginal heat source, i.e. the source that is actually replaced when heat is produced by the biogas engine. Yet, the marginal heat source may be variable in function of the biogas plant location. For example, if the biogas plant is connected to the district heating grid, then the heat from the biogas plant replace the marginal energy source of the combined heat and power (CHP) producing plant. This marginal energy source is then likely to be coal or natural gas. On the other hand, the biogas plant may also be connected to the natural gas grid and inject the (upgraded) biogas in the grid, as this is likely to be the case for many plants in Denmark in the future (Jensen, 2009b; Utoft, 2009), in which case the biogas would replace natural gas. Another possibility is that the biogas plant may be located in a remote location and thereby replace heat that was produced through individual boiler. There is then a range of possibilities regarding the marginal heat source for these individual boilers: wooden pellets, straw, fuel-oil. In this study, based on what is envisioned to be the future trends, it is assumed that the biogas plant is not located in a remote location, i.e. it is (or can be) connected to the district heating grid or the natural gas grid. This involves that the marginal heat source is likely to be whether coal (generating heat through CHP) or natural gas (generating heat through CHP or as used through the natural gas grid).

Coal through CHP was assumed to be the marginal heat avoided in this project (Ecoinvent process “Heat, at hard coal industrial furnace 1-10MW/RER U”, described in Dones et al. (2007), table 11.10,p.224), but a sensitivity analysis was carried out for:

- Natural gas (through CHP; Ecoinvent process: “Heat, natural gas, at boiler condensing modulating >100kW/RER U”, described in Faist-Emmernegger et al. (2007), table 13.10, p.161);

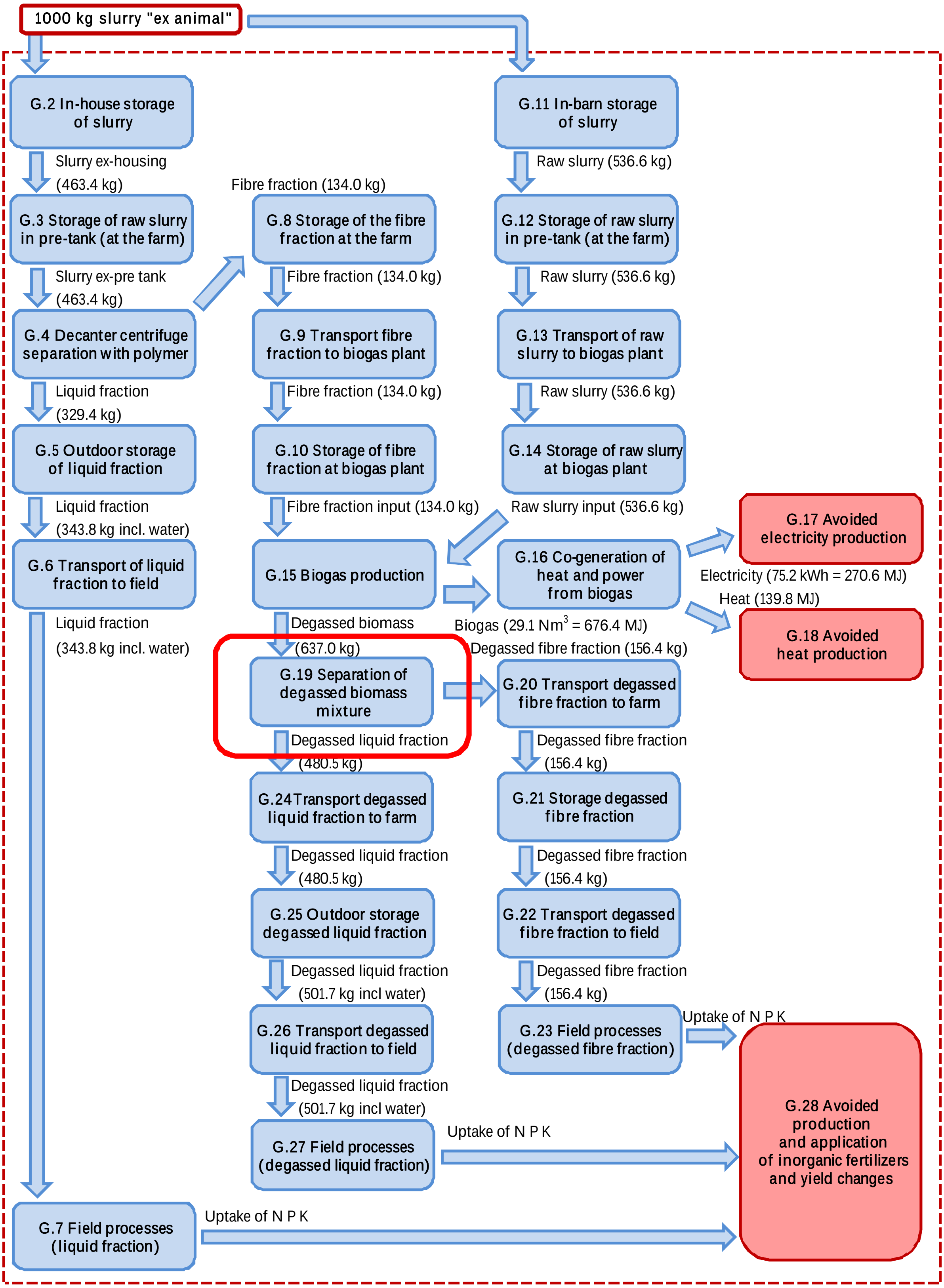
- Natural gas (through the natural gas grid; Ecoinvent process: “Natural gas, high pressure, at consumer/DK U”, described in Faist-Emmernegger et al. (2007), table 8.19, p.89-90). In this case, it is not heat that is avoided but the use (and production) of natural gas. This also means that no cogeneration takes place (no electricity or heat are produced, only biogas). This sensitivity analysis does not include the upgrading process (and neither the losses occurring during this process), so it should be considered that the actual environmental benefits are slightly lower than the results presented by this sensitivity analysis.

It can be noticed that the processes used for modelling CHP production are processes corresponding to production of heat only, for coal and for natural gas. This means that the co-production of electricity at the CHP plant is not accounted for. Though this is not correct, it was judged to be the option allowing to reflect the environmental consequences of this scenario the most accurately. This is because the Ecoinvent processes for co-generation of heat and electricity are allocated, which is incompatible with the methodology used throughout this study, i.e. consequential life cycle assessment, so it would be inconsistent to use allocated data at this stage. Un-allocating these data would however be well beyond the framework of this project, would be highly uncertain and would require external validation in order to meet the high quality standards of the Ecoinvent data. Therefore, the best compromise was judged to use the high quality data of the Ecoinvent database, but for generation of heat only, even though this project considers that CHP production is replaced and not heat only. This must be taken into account when interpreting the results.

As described in section F.16, not all the heat surpluses from the biogas plant can be used for fulfilling the national heat demand, but only 60 % of these surpluses, as there are periods where the heat demand is rather low as compared to the heat produced.

As a sensitivity analysis, the extreme situation where the surplus heat produced at the biogas plant is not used at all (i.e. no replacement) is investigated.

Process G.19: Separation of the degassed biomass mixture



G.19 Separation of digested biomass AFTER the Biogas plant

G.19.1 Separation indexes

The separation technology considered after the biogas plant is the same as in Annex F, section F.19. Therefore, a GEA Westfalia decanter centrifuge (model UCD 305) was used, without polymer addition. Material consumption data and electricity consumption data are therefore identical to those described in Annex F (section F.4.5 and F.4.4, respectively). As in Annex F, data for the separation efficiencies comes from Frandsen (2009) and from Møller et al. (2007b) in the case of Cu and Zn (see table F.25, Annex F). However, the separation efficiencies for Cu and Zn used in this Annex are different from those presented in Annex F since Møller et al. (2007b) present distinct data for cattle and pig slurry.

Moreover, the separation efficiency for the total mass is different from the data presented in table F.25 as it is adjusted based on the slurry type, as described in section G.4.2. Accordingly, as for the separation before the biogas plant, it was assumed that the DM of the solid fraction coming out of the separator would remain approximately constant independently of the water content of the degassed slurry. Based on this, the total mass of fibre fraction can be evaluated, and thereby the separation index for the total mass. Since the amount of DM in the resulting fibre fraction was measured (26.71 %, which means that there is 267.1 kg DM per 1000 kg of fibre fraction according to table 4 in Frandsen (2009)), and since the DM content of the input degassed biomass is known (107.73 kg DM per kg degassed biomass, table G.23), the mass of fibre fraction produced can be calculated. This amounts to 245.638 kg fibre fraction per 1000 kg degassed biomass[20], which means that 24.56 % of the initial mass is found in the solid fraction. The remaining mass is then going in the liquid fraction, corresponding to 75.44 % (i.e. 100 % - 24.56 %).

The separation indexes considered for the post-biogas separation are summarized in table G.26.

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[20] The input degassed slurry to separate contains 107.73 kg DM/1000 kg degassed biomass (table G.23). Yet, 60.9% of the DM ends up in the fibre fraction with the separation indexes considered (see table G.26) i.e. 107.73 kg * 60.9% = 65.61 kg DM per 1000 kg degassed biomass. As the fibre fraction contains 267.1 kg DM per 1000 kg fibre fraction (due to measurements, see table 4 in Frandsen (2009)), the total amount of fibre fraction is: 65.61 kg DM / 1000 kg degassed biomass * 1000 kg fibre fraction/ 267.1 kg DM = 245.638 kg fibre fraction per 1000 kg degassed biomass.

Table G.26.
Separation indexes for separation of cow slurry AFTER the biogas plant. (polymer is not added). Data from Frandsen (2009), unless otherwise specified.

	Fibre fraction	Liquid fraction
Total mass [a)]	24.56%	75.44%
Dry matter (DM)	60.9%	39.1%
Total-N	21.2%	78.8%
Ammonium-N	14.6%	85.4%
Phosphorous (P)	66.2%	33.8%
Potassium (K)	9.7%	90.3%
Carbon (C) [b)]	60.9%	39.1%
Cooper (Cu) [c)]	6.7%	93.3%
Zinc (Zn) [c)]	25.3%	74.7%

a) This is a calculated value, see text.
b) No data. Assumed to be the same as DM.
c) From Møller et al. (2007b). Data for centrifuge, cattle slurry no.5 used (table 3).

G.19.2 Mass balances

The mass balances of the degassed biomass mixture before and after the separation are presented in table G.27. It should be highlighted that no data as regarding the emissions occurring during the separation process has been found, as it was also the case with the separation before the biogas is produced (i.e. process G.4). This lack of data is particularly critical as regarding ammonia emissions, which are likely to occur given the volatile nature of ammonia. Yet, it appears reasonable to assume that all the emissions likely to occur during the separation are occurring in later stages anyway, so considering them at this stage or at later stages does not change the overall results.

The life cycle data for the separation post biogas production are presented in table G.28.

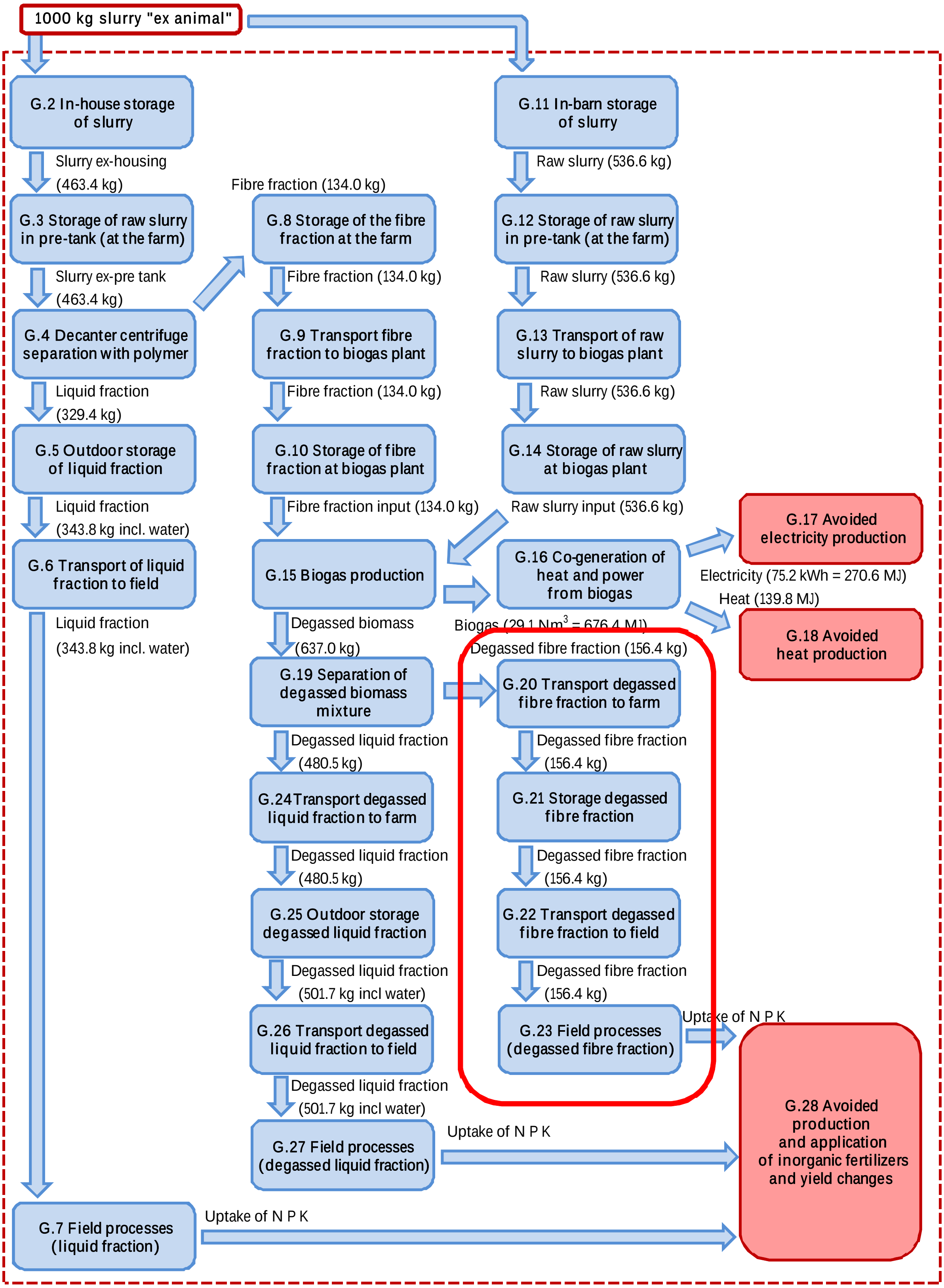
Table G.27.
Mass balances for separation of the degassed biomass.
Per 1000 kg of degassed biomass mixture "ex-digester".

	Amount in degassed biomass mixture BEFORE separation	Separation index from table G.26	Mass Balance: Amount transferred to the fibre fraction	Mass balance: Amount transferred to the liquid fraction	Composition of the degassed fibre fraction AFTER separation Fibre fraction * 1000 / 245.6 kg	Composition of degassed liquid fraction AFTER separation Liquid fraction * 1000 kg / 754.4 kg
	[per 1000 kg ex-digester]		[per 1000 kg ex-digester]	[per 1000 kg ex-digester]	[kg per 1000 kg fibre fraction]	[kg per 1000 kg liquid fraction]
Total mass	1000 kg slurry ex-digester	24.56%	245.6 kg	1000 kg – 245.6 kg = 754.4 kg	1000 kg Degassed fibre fraction	1000 kg degassed liquid fraction
Dry matter (DM)	107.73 kg	60.9%	107.73 kg *60.9% = 65.61 kg	107.73 kg *(100-60.9)% = 42.12 kg	267.1 kg	55.83 kg
Total-N	7.64 kg	21.2%	7.64 kg *21.2% = 1.62 kg	7.64 kg *(100-21.2)% = 6.02 kg	6.60 kg	7.98 kg
Total-P	1.381 kg	66.2%	1.381 kg *66.2% = 0.914 kg	1.381 kg *(100-66.2)% = 0.467 kg	3.72 kg	0.62 kg
Potassium (K)	5.828 kg	9.7%	5.828 kg *9.7% =0.565 kg	5.828 kg *(100-9.7)% = 5.263 kg	2.30 kg	6.98 kg
Carbon (C)	45.699 kg	60.9%	45.699 kg *60.9% = 27.83 kg	45.699 kg *(100-60.9)% = 17.87 kg	113.3 kg	23.69 kg
Copper (Cu)	0.0111 kg	6.7 %	0.0111 kg *6.7% = 0.0007 kg	0.0111 kg *(100-6.7)% = 0.0104 kg	0.003 kg	0.014 kg
Zinc (Zn)	0.0216 kg	25.3%	0.0216 kg *25.3% = 0.0055 kg	0.0216 kg *(100-25.3)% = 0.0161 kg	0.022 kg	0.0213 kg

Table G.28.
Life cycle data for separation (decanter centrifuge) after the anaerobic digestion. Data per 1000 kg slurry (ex-digester). Dairy cows digested slurry.

	Dairy cows degassed slurry	Comments
Input		
Slurry (ex-digester)	1000 kg	Degassed biomass ex-digester.
Output		
Fibre fraction	245.6 kg	
Liquid fraction	754.4 kg	
Energy consumption		
Electricity	2.184 kWh	See table F.9 (Annex F)
Material consumption		
Separation equipment	included	See table F.10 (Annex F)
Emissions to air		
Carbon dioxide (CO_2)		No data
Methane (CH_4)		No data
Non-methane volatile organic compounds (NMVOC)		No data
Ammonia (NH_3-N)		No data.
Nitrous oxide (N_2O-N)		No data
Nitrogen oxides (NO_X)		No data
Nitrogen monoxide(NO)		No data
Nitrogen(N_2)		No data
Particulates		No data
Hydrogen sulphide (H_2S)		No data
Sulphur dioxide (SO_2)		No data
Odour		No data
Emissions to water		
		No emissions to water

Processes G.20 to G.23: fate of the degassed fibre fraction



G.20 Transport of the degassed fibre fraction to the farm

The degassed fibre fraction will be transported to a farm where a fertilizer rich in P is needed. The transport distance from the biogas plant to this farm was modelled as 100 km. This distance takes into account the assumption that the degassed fibre fraction is not transported between the eastern and western parts of Denmark, as this would not pays off. This is in conformity with Dalgaard et al. (2006).

The fibre fraction is transported by trucks. The transport is modelled by use of the Ecoinvent process “Transport, lorry >32t, EURO3” (Spielmann et al., 2007; table 5-124, p.96).

G.21 Storage of the degassed fibre fraction

G.21.1 General description

In this study, it is assumed that the degassed fibre fraction is stored in a covered heap, outdoor. The effect of covering has tremendous impacts on the resulting emissions, as this contribute to reduce the degradation of organic matter favoured when the heap is exposed to air, and thereby the resulting gaseous emissions to the environment.

In an experiment where air-tight covered heap from solid fraction of swine manure were compared to uncovered heap, Hansen et al. (2006) observed emissions reductions of 12 %, 99 % and 88% for NH_3, N_2O and CH_4 when the heap were covered. In another study carried out by Dinuccio et al. (2008), the authors concluded from their results that, because of the emissions occurring during the (uncovered) storage phase, mechanical separation of cattle and pig slurry has the potential to increase the emissions of CO_2 equivalents by up to 30 % as compared to raw slurry. Amon et al. (2006) raise similar concerns applying particularly for the fibre fraction.

In this study, the fibre fraction is stored in heap lying on a concrete slab. The heap is covered by a polyethylene plastic sheet. This is considered as the best management practice, as this does not involve any specific energy requirements, and as this limits the C losses occurring when the heap is not covered (i.e. through the natural composting thereby occurring). This also contributes to limit the ammonia volatilization and complies with the Danish law stipulating that the stores of solid manure that do not receive daily input of materials have to be covered (Miljøministeriet, 2006).

Fibrous fractions of separated slurry that are not used for biogas production are normally stored temporally for about a week (Hansen, 2009). During that temporal storage phase, new material is regularly added until the storage capacity is full. The fibre fraction is then moved to a static store, where it is, in practice, stored for up to half a year (Hansen, 2009).

In this study, it is considered that the truck delivering the degassed fibre fraction from the biogas plant will come to the farm only once, with the amount needed by the farmer. Therefore, only static storage is involved.

G.21.2 Material consumption

Table G.29 presents the material consumption for the storage of the degassed fibre fraction. The dimensions of the storage platform used for calculating the amount of concrete needed are based on the data found in Petersen and Sørensen (2008). The annual amount of degassed fibre fraction to store is also based on Petersen and Sørensen (2008). The height of the heap is 2 m (based on Petersen and Sørensen, 2008).

Table G.29.
Material consumption for the storage of the degassed fibre fraction

Materials	Amount of material in plant	Estimated life time	Amount of degassed fibre fraction per year [kg degassed fibre fraction per year]	Amount of degassed fibre fraction in a life time [kg degassed fibre fraction in a life time]	Amount of material [per 1000 kg degassed fibre fraction]
Storage of degassed fibre fraction					
Concrete (H: 0.125 m x W: 5 m x L: 120 m)	75 m^3	40 years	520 000 kg / y	20 800 000 kg	0.003606 m^3
Polyethylene (LDPE) – 0.15 mm [a)]	190 kg	1 year	520 000 kg / y	520 000 kg	0.3654 g

a)The density considered for polyethylene is 0.96 g/cm^3.

G.21.3 Water addition

Since the heap is covered, it is considered that there is no water addition during storage. This in fact may not be exactly true since the fibre fraction might absorb some moisture from the air.

G.21.4 CH_4 emissions

Amon et al. (2006) measured, for the uncovered storage of a fibre fraction from cattle slurry, CH_4 emissions of 510.6 g CH_4 per m^3 slurry. The density of their fibre fraction is not specified, but assuming a density of 600 kg/m^3 (as in table G.19) yields CH_4 emissions of 0.851 kg per 1000 kg fibre fraction. This was for a non-degassed fibre fraction stored during 80 days under warm conditions (mean slurry temperature of 17°C).

In the study of Dinuccio et al. (2008), for 30 days of open storage, the authors measured CH_4-C emissions for the fibre fraction of cattle slurry corresponding to 0.77 % and 0.23 % of the VS for fibre fraction stored at 5 and 25 °C, respectively. This is for a non-degassed fibre fraction. In the present study, these figures would correspond to CH_4 emissions of 2.20 and 0.656 kg CH_4 per1000 kg fibre fraction (assuming the VS content corresponds to 80 % of the DM).

In Annex F (section F.21.4), it was assumed that CH_4-C emissions corresponded to 0.17 % of the C content of the fibre fraction ex-separation. This estimate was based on a study of Hansen et al. (2006) for covered storage of degassed fibre fraction from pig slurry. In the present case, this would correspond to 0.257 kg of CH_4 per 1000 kg fibre fraction. This is the estimate that will be used in the present Annex. Using value that were obtained with degassed fibre fraction from pig slurry may not be exactly representative of the actual emissions occurring with digested fibre fraction from cow slurry, but with no better available data, it is nevertheless judged as the best estimate to reflect the emissions occurring under covered storage.

G.21.5 CO_2 emissions

In the study of Dinuccio et al. (2008), for 30 days of open storage, the authors measured CO_2-C emissions for the fibre fraction of cattle slurry corresponding to 16.4 % and 25.6 % of the VS for fibre fraction stored at 5 and 25 °C, respectively. This is for a non-degassed fibre fraction. In the present study, these figures would correspond to CO_2 emissions of 128.4 and 200.4 kg CH_4 per1000 kg fibre fraction (assuming the VS content corresponds to 80 % of the DM).

The study of Dinuccio et al. (2008) clearly shows that most of the C losses from the covered storage of cattle slurry fibre fraction occurred through CO_2. In fact, for a non-covered storage at 5°C, the ratio between the emissions of CO_2-C and CH_4-C as measured by Dinuccio et al. (2008) is 21.30, while it is 111.30 for a storage at 30°C.

In Annex F, based on a study of covered degassed fibre fraction from pig slurry carried out by Hansen et al. (2006), it was assumed that CO_2-C = 1.9 % of the C content of the fibre fraction ex-separation. This estimate will also be used in the present annex, as the fibre fraction is covered (and thereby is likely to emit less than the amount reported in the literature for uncovered storage). For the present study, this corresponds to a CO_2 emission of 7.89 kg per 1000 kg degassed fibre fraction.

G.21.6 NH_3 emissions

According to Petersen and Sørensen (2008), a “significant proportion” of the N losses during the storage of degassed fibre fraction shall be attributed to NH_3-N losses. This is in line with the results of Amon et al. (2006), who report a net increase in total NH_3 emissions from stored cattle fibre fraction as opposed to stored raw cattle slurry.

Amon et al. (2006) measured 287.8 g NH_3 per m^3 fibre fraction, which corresponds to 0.480 kg NH_3 per 1000 kg fibre fraction, assuming a density of 600 kg/m^3 (as in table G.19). This is, however, for non-covered and non-degassed fibre fraction, stored during 80 days, with a mean slurry temperature of 17 °C. In the present project, this would correspond to approximately 6 % of the initial N content of the fibre fraction.

Dinuccio et al. (2008) measured NH_3-N losses corresponding to 6.03 % and 5.21 % of the initial N content, for cattle fibre fraction stored at 25 °C and 5 °C, respectively, during 30 days. In this study, this corresponds to emissions of 0.398 and 0.344 kg NH_3-N per 1000 kg fibre fraction. This is also for non-covered and non-degassed fibre fraction.

In this study, the heap is covered, so NH_3-N emissions are expected to be lower than those reported in the literature for non covered (and non-degassed) heaps. Yet, Hansen (2009) recommends to use a value of NH_3-N emissions corresponding to 13 % of the initial N (as it was done in Annex F, for pig degassed fibre fraction under covered storage, section F.21.3). This is based on recent experiments showing that cattle fibre fraction composts as much as pig fibre fraction (Hansen, 2009). The results of Dinuccio et al. (2008) in fact tend to acknowledge that, as the authors measured similar NH_3-N losses for both cow and pig fibre fractions. However, a value of 13 % of the initial N is higher than the values reported in recent studies for uncovered storage of non-degassed fibre fraction.

A value of 5.75 % of the N in the degassed fibre fraction ex-storage will therefore be use for estimating NH_3-N emissions. This corresponds of the average of the values above-mentioned from the studies of Amon et al. (2006) and Dinuccio et al. (2008), for temperatures between 5 and 25 °C. This value should be considered as a rough estimate.

G.21.7 N_2O emissions

Covering allow to restrict the air inflow over the heap and therefore the potential for nitrification (and thereby denitrification) processes. In fact, Hansen et al. (2006) observed emissions reduction of 99 % for covered heap as compared to uncovered heap.

Dinuccio et al. (2008) did not succeed to measure significant amount of N_2O emissions during open storage of stored fibre fraction from cattle manure. This was true for both 5 and 25°C storage temperature. Amon et al. (2006) measured N_2O emissions of 13.2 g per m^3 fibre fraction for separated cattle slurry. Assuming a density of 600 kg/m^3 (as in table G.19), this corresponds to 0.022 kg N_2O per 1000 kg fibre fraction (i.e. 0.007 kg N_2O-N per 1000 kg fibre fraction). When applied to this study, it corresponds to N_2O-N emissions of 0.106 % of the initial N content

In Annex F, N_2O-N emissions were estimated as 0.04% of the initial N of the fibre fraction, based on a study carried out by Hansen et al. (2006) with covered heap from degassed fibre fraction from pigs. This estimate is also used in the present annex, as there are no other data for degassed cow fibre fraction stored in covered heap. It should therefore be seen as a rough estimate.

The indirect N_2O emissions are calculated as in Annex A, i.e. based on IPCC guidelines (IPCC, 2006). Therefore, the indirect N_2O emissions are calculated as 0.01 kg N_2O-N per kg (NH_3-N + NO_x-N) volatilized.

G.21.8 NO, NO_x and N_2 emissions

As it was not possible to find data for NO, NO_2 and N_2 emissions, the same hypothesis as those detailed in section A.2.3 of Annex A were used, i.e. based on the study of Dämmgen and Hutchings (2008). In their study, they assumed that the emission of nitrogen monoxide (NO) is the same as the direct emission of nitrous oxide (N_2O) (measured as NO-N and N_2O-N). Furthermore, they assumed that emission of nitrogen (N_2) is three times as high as the direct emissions of nitrous oxide (N_2O) (measured as N_2-N and N_2O-N).

As regarding the total NO_x emissions ($NO_x = NO + NO_2$), it was assumed, as in Annex A, that $NO_x = NO$. This is because it has not been possible to find data on NO_2.

G.21.9 Life cycle data and mass balances for storage of degassed fibre fraction

Table G.30 summarizes the LCA data for the storage of degassed slurry, while table G.31 presents the mass balances. The estimation for C in the degassed fibre fraction after storage presented in table G.31 may overestimate the actual amount of C. This is because CH_4 and CO_2 emissions considered were based on the study of Hansen et al. (2006). Yet, in that study, a significant portion of the C was lost and could not be accounted for as CH_4 or CO_2 emissions. This non-accounted for portion is 4.9 % of the initial C content, for covered heap (Hansen et al., 2006), as compared to measured 0.17 % for CH_4-C and 1.9 % for CO_2-C. In the present study, these “unexplainable losses” are not included (this would correspond to 5.55 kg C/1000 kg degassed fibre fraction in the present project).

In table G.31, it can be noticed that the change of DM is estimated as the losses of N and C. As explained in section G.5.8, it is acknowledged that this is a rough estimation, as other elements of greater molecular weight may also be lost (e.g. dissolved O_2). The estimated DM change shall therefore be seen as a minimum change, the actual DM change may in fact be greater than the one taken into account in this study.

Table G.30
Life cycle data for storage of the degassed fibre fraction. All data per 1000 kg of degassed fibre fraction.

	Fibre fraction ex-separation	Comments
Input		
Degassed fibre fraction ex-separation	1000 kg	The emissions are calculated relatively to this.
Concrete slab and polyethylene for storage	Included	See text.
Output		
Degassed fibre fraction “ex-storage”	1000 kg	No water is added. See text.
Energy consumption		
Electricity	None	See text.
Emissions to air		
Carbon dioxide (CO_2)	7.89 kg	CO_2-C = 1.9 % of C in degassed fibre fraction ex-separation, see text.
Methane (CH_4)	0.257 kg	CH_4-C = 0.17 % of C in degassed fibre fraction ex-separation, see text.
Ammonia (NH_3-N)	0.3795 kg	NH_3-N = 5.75 % of total N in degassed fibre fraction ex-separation, see text.
Direct emissions of Nitrous oxide (N_2O-N)	0.00264 kg	N_2O-N = 0.04 % of total N in degassed fibre fraction ex-separation, see text.
Indirect emissions of Nitrous oxide (N_2O-N)	0.00382 kg	0.01 kg N_2O–N per kg (NH_3–N + NO_X–N) volatilised (IPCC, 2006, table 11.3).
Nitrogen monoxide (NO-N) (representing total NO_X)	0.00264 kg	Estimate based on Dämmgen and Hutchings (2008), consisting of assuming that NO-N = (direct) N_2O-N * 1, see text.
Nitrogen dioxide (NO_2-N)	No data	No data
Nitrogen (N_2-N)	0.00792 kg	Estimate based on Dämmgen and Hutchings (2008), consisting of assuming that N_2-N = (direct) N_2O-N * 3.
Discharges to soil		
	None	Assumed to be insignificant, as the heaps are covered.

Table G.31
Mass balances for storage of degassed fibre fraction

	Degassed fibre fraction composition AFTER the separation (from table G.27) [kg per 1000 kg degassed fibre fraction]	Mass balance: Change during storage of fibre fraction [kg]	Mass balance: Amount after storage of fibre fraction [kg]	Composition of degassed fibre fraction AFTER storage [kg per 1000 kg degassed fibre fraction AFTER storage]
Total mass	1000 kg	No change	1000 kg	1000 kg
Dry matter (DM)	267.1 kg	- 2.74 kg c)	264.36 kg	264.36 kg
Total-N	6.60 kg	- 0.393 kg a)	6.21 kg	6.21 kg
Total-P	3.72 kg	No change	3.72 kg	3.72 kg
Potassium (K)	2.30 kg	No change	2.30 kg	2.30 kg
Carbon (C)	113.3 kg	- 2.346 kg b)	111.0 kg	111.0 kg
Copper (Cu)	0.003 kg	No change	0.003 kg	0.003 kg
Zinc (Zn)	0.022 kg	No change	0.022 kg	0.022 kg

[a] Changes in total N: 0.3795 kg NH_3-N + 0.00264 kg N_2O-N + 0.00264 kg NO-N + 0.00792 kg N_2-N = 0.393 kg N

[b] Changes in total C: 7.89 kg CO2 * 12.011 [g/mol] /44.01 [g/mol] + 0.257 kg CH4 * 12.011 [g/mol] /16.04 [g/mol] = 2.74 kg C

[c] The change in DM is assumed to be identical to the sum of the loss of N and C

G.22 Transport of the degassed fibre fraction to the field

The transport of the degassed fibre fraction to the field is identical to the process described in section G.6 (transport of the liquid fraction to the field).

This means that the process "Transport, tractor and trailer" from the Ecoinvent database has been used (Nemecek and Kägi, 2007, p.204), for a distance of 10 km. This includes the construction of the tractor and the trailer.

G.23 Field processes for the degassed fibre fraction

G.23.1 General description

For this process, the data from the Ecoinvent process "solid manure, loading and spreading, by hydraulic loader and spreader" (Nemecek and Kägi, 2007, p.200) has been used for the emissions occurring during spreading. This includes, among other, the diesel consumption and the consumption of spreading equipment.

G.23.2 Emissions of CH_4 and CO_2

The CH_4 emissions on the field are assumed to be negligible, as the formation of CH_4 requires an anaerobic environment, which is, under normal conditions, not the case in the top soil.

CO_2 emissions and C-binding in the soil are modelled by the dynamic soil organic matter model C-TOOL (Petersen et al., 2002; Gyldenkærne et al., 2007).

G.23.3 Emissions of NH_3

Emissions of NH_3 are estimated based on the data for solid slurry presented in a recent publication from Hansen et al. (2008). Assuming the application takes place in the spring and that the applied degassed fibre fraction is ploughed or harrowed within 6 hours after the application, the overall NH_3 losses are calculated as 40 % of the NH_4-N (based on table 18 from Hansen et al., 2008). Yet, the values presented by Hansen et al. (2008) assumed that NH_4-N corresponds to 25 % of the N content of the solid slurry ex-storage.

Applied to the data of the present study, this means that NH_3 emissions corresponds to 0.621 kg (40% * 6.21 kg N * 25 %). The NH_3-N losses therefore correspond to 0.5107 kg.

G.23.4 Emissions of N_2O

The direct and indirect N_2O emissions were based on IPCC guidelines (IPCC, 2006), as in Annex A, section A.5. This considers that the direct N_2O emissions correspond to 0.01 kg N_2O-N per kg N ex-storage, while the indirect N_2O-N emissions are estimated as 0.01 kg N_2O-N per kg (NH_3-N + NO_X-N volatilized). The indirect N_2O-N emissions based on nitrate leaching are also considered, based on IPCC guidelines (IPCC, 2006), thereby they are estimated as 0.0075 kg N_2O-N per kg N leaching.

G.23.5 Emissions of NO_X and N_2-N

As in previous sections, the emissions of NO and NO_2 are combined as NO_X-emissions, as separate data on NO and NO_2 has not been available. According to Nemecek and Kägi (2007) (page 36) the NO_X emissions can be estimated as: $NO_X = 0.21 * N_2O$. When taking the molar weights into consideration this corresponds to NO_X–N = 0.1 * N_2O-N. It is considered to be a “rough expert estimate”, but since the relative contribution has minor significance for the overall results, it is considered to be adequate.

The N_2-N emissions are based on the estimates from SimDen (Vinther, 2004). For soil type JB3 the N_2-N:N_2O-N ratio is 3:1 and for soil type JB6 the N_2-N:N_2O-N ratio is 6:1.

G.23.6 Calculation of degassed fibre fraction fertilizer value

The calculation of the fertilizer value of the degassed fibre fraction is presented and detailed in section G.28.

G.23.7 Nitrate leaching

The content of C of the degassed fibre fraction is rather high, which gives rise to a substantial increase in soil C, after 10 years the C content in the soil is still increased with 26.4 (JB3) and 27.8 (JB6) kg C per 1000 kg fiber fraction, according to C-TOOL. The majority of the C in the degassed fibre fraction is released as CO_2 (table G.32). The above increase in soil C gives rise to a modeled increase in soil N of 10% of the C increase, i.e. 2.64 (JB3) and 2.78

(JB6) kg N per 1000 kg degassed fibre fraction. According to this modeling, 3.57 (JB3) and 3.43 (JB6) kg N are left for both plant uptake and all N losses (before gaseous losses).

After the gaseous losses (table G.32), there is 2.81 (JB3) and 2.48 (JB6) kg N left for harvest and leaching. For the 100 years values, there is, after the gaseous losses, 5.4798 (JB3) and 5.4392 (JB6) kg N left for harvest and leaching. For simplicity, the distribution of the surplus between harvest and leaching is assumed to be as for cattle slurry (table A.16, Annex A), which gives the leaching values of table G.32.

When transforming the above 10-year considerations to 100-year values, the additional mineralisation of N is calculated first, utilising C-TOOL. The mineralized N is assumed to be subject to denitrification, with the same factor as for N amendment. The plant uptake value of mineralized N relative to mineral fertilizer is assumed to be an average of 65.3 % on JB3 and 73.0 % on JB6, in accordance with the calculations in Annex A, section A.5. The remainder after denitrification and harvest removal is assumed to go to N leaching, which results to the 100-year figures in table G.32.

G.23.8 Phosphorus leaching

For P leaching, the same assumptions as those used in Annex A were used, i.e., 10% of the P applied to field has the possibility of leaching and 6% of this actually reach the aquatic recipients, based on Hauschild and Potting (2005).

G.23.9 Cu and Zn fate

As in Annex A, it is considered that the entirety of the Cu and Zn applied will leach through the water compartment.

G.23.10 Fate of the polymer

The fate of the polyacrylamide polymer (PAM) used in the separation process described in section G.4 is considered here, assuming that no losses occurred and that 100 % of the polymer is transferred to the degassed fibre fraction. This assumption is made for simplification purposes only, but is not of importance, as both fractions end up to be spread in the field. As described in section G.4, an amount of 0.60 kg of polymer was used per 1000 kg of slurry ex pre-tank input.

As extensively detailed in Annex F, it is considered that 100 % of the PAM present in the applied degassed fibre fraction is accumulating in the environment.

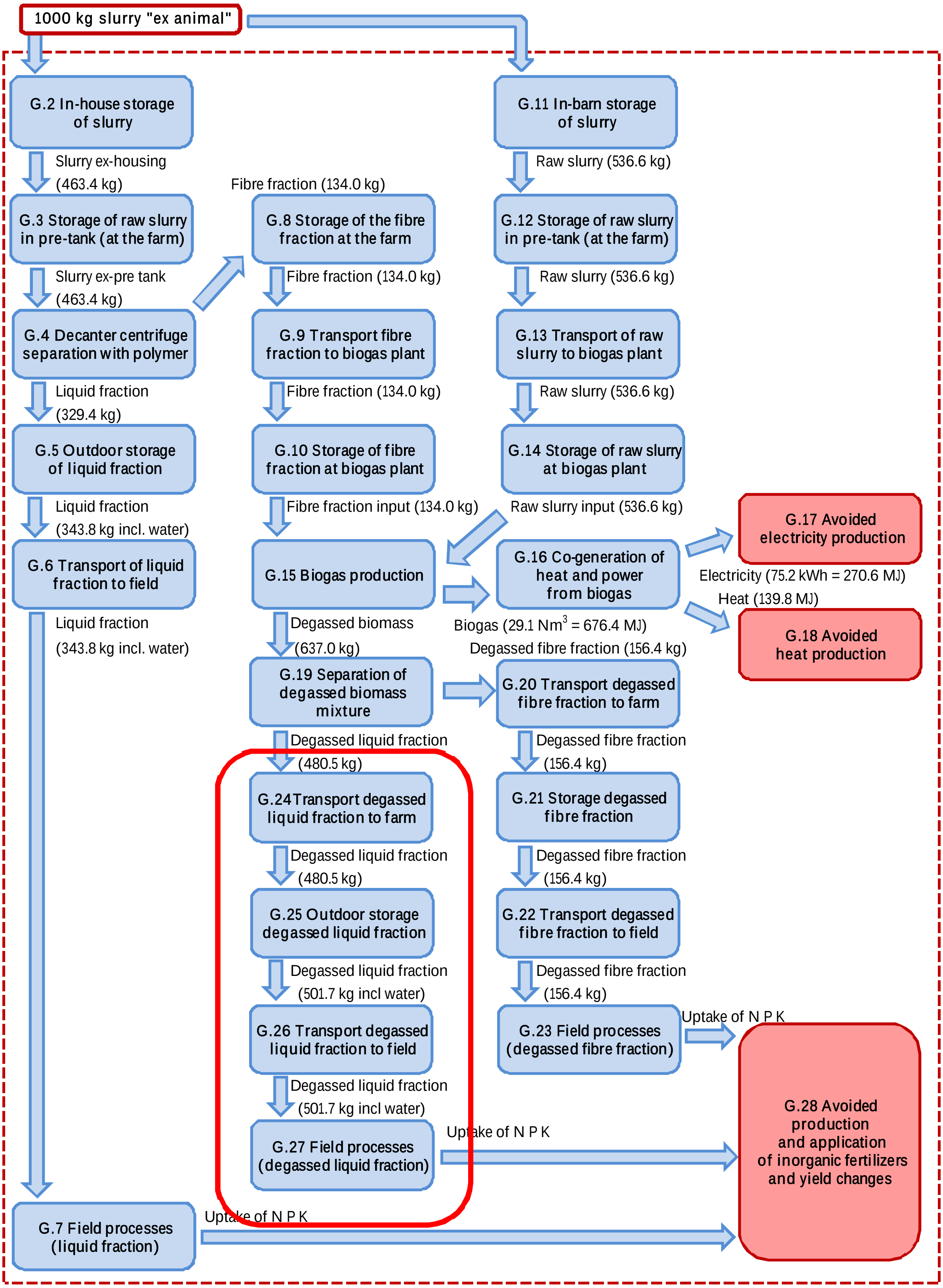
G.23.11 Life cycle data for field application of degassed fibre fraction and field processes

Table G.32 presents the life cycle data for the application of degassed ex-storage fibre fraction on the field.

Table G.32.
Life cycle data for application of degassed fibre fraction and field processes. All data per 1000 kg of "digested fibre fraction ex-outdoor storage". Dairy cow degassed fibre fraction ex-storage.

	Degassed fibre fraction after storage	Comments
Input		
Degassed fibre fraction "ex-storage"	1000 kg	
Output		
Slurry on field, fertiliser value	Fertiliser replacement value: N, P and K	See section G.28.
Energy consumption		
Diesel for spreading equipment	0.531 kg of diesel	Based on the Ecoinvent process "solid manure, loading and spreading, by hydraulic loader and spreader".
Emissions to air		
Carbon dioxide (CO_2) Soil JB3 Soil JB6	 310.3 (380.1) kg 305.0 (378.6) kg	Modelled by C-TOOL (Gyldenkærne et al, 2007). 10 year value and 100 year in parenthesis.
Methane (CH_4)	Negligible	The CH_4 emission on the field are assumed to be negligible, as the formation of CH_4 requires anoxic environment (the field is aerobic) (Sherlock et al., 2002).
Ammonia (NH_3-N) after application	0.5107 kg	NH_3 emissions estimated as 40 % of the NH_4-N applied. The NH_4-N is assumed to be 25 % of the N content of the degassed fibre fraction ex-storage (see text). NH_3-N emissions therefore correspond to: 40% * 6.21 kg * 25 % * (14.007 g/mol N / 17.031 g/mol NH_3) = 0.5107 kg NH_3-N.
Direct emissions of Nitrous oxide (N_2O-N)	0.0621 kg [0.0186 – 0.186]	0.01 [0.003 - 0.03] kg N_2O-N per kg N "ex-storage" for application of animal wastes to soil, based on IPPC (IPCC 2006; table 11.1).
Indirect emissions of Nitrous oxide (N_2O-N) Soil JB3 Soil JB6	0.00517 kg 0.011 kg (0.021 kg) 0.008 kg (0.017 kg)	Indirect emissions due to emissions of ammonia and NO_X: 0.01 kg N_2O–N per kg (NH_3–N + NO_X–N) volatilised (IPCC, 2006) Indirect emissions due to nitrate leaching: 0.0075 kg N_2O–N per kg N leaching (IPCC, 2006). 10 year value and 100 year in parenthesis.
Nitrogen oxides (NO_x-N)	0.00621 kg	NO_X–N = 0.1 * N_2O-N according to Nemecek and Kägi (2007)
Nitrogen (N_2-N) Soil JB3 Soil JB6	 0.1863 kg 0.3726 kg	Estimated from the SimDen model ratios between N_2-N and N_2O-N (see text): 3:1 for soil JB3 and 6:1 for soil JB6.
Discharges to soil		
Nitrate leaching Soil JB3 Soil JB6	 1.50 (2.81) kg N 1.06 (2.26) kg N	Estimated from N partitioning (see text and table A.16, Annex A). 10 year values, numbers in parenthesis are 100 year values.
Phosphate leaching	0.372 kg P	10 % of the P applied to field (Hauschild and Potting, 2005).(Only 6 % of this reach the aquatic environment)
Copper (Cu)	0.003 kg	See table G.31
Zinc (Zn)	0.022 kg	See table G.31

Processes G.24 to G.27: fate of the degassed liquid fraction



G.24 Transport of the degassed liquid fraction to the farm

The transport of the degassed liquid fraction back to the farm is identical to the process described in section G.13 (transport of raw slurry to biogas plant).

This means that a distance of 5 km is taken into account between the farm and the biogas plant. As transport distance is not anticipated to have a considerable influence on the environmental impacts in the overall scenario (based on the results obtained by Wesnæs et al., 2009), no sensitivity analysis was carried out for a greater transport distance.

The degassed liquid is transported by trucks. The transport is modelled by use of the Ecoinvent process "Transport, lorry >32t, EURO3" (Spielmann et al., 2007; table 5-124, p.96).

G.25 Outdoor storage of the degassed liquid fraction

G.25.1 General description

The outdoor storage of the degassed liquid fraction is assumed to be stored in an outdoor concrete tank covered with a floating layer consisting of 2.5 kg of straw per 1000 kg slurry stored (as for process G.5). As in section G.5.1, the life cycle data of straw production are not included in this study, as straw is regarded as a waste product from cereal production (rather than a co-product).

G.25.2 Addition of water

The degassed liquid fraction will be diluted by precipitation in the same amount as described in G.5.2, i.e. a total of 44 kg of water.

G.25.3 Electricity consumption

As with the non degassed liquid fraction in section G.5, the electricity for pumping and stirring is taken from table A.10 (Annex A) and is adjusted by a reduction of 50 %, in order to account for the fact that the liquid fraction will offer less resistance during the pumping and stirring than does the raw slurry. This is further detailed in section G.5.

The electricity consumption thus involves: the consumption for stirring when straw is added (1.2 kWh per 1000 kg slurry), the consumption for stirring (1.2 kWh per 1000 kg slurry) and pumping (0.5 kWh per 1000 kg slurry), before application to the field. This gives an electricity consumption of 2.9 kWh per 1000 kg slurry, on which a factor of 50 % is applied, which results in an electricity consumption of 1.45 kWh per 1000 kg degassed liquid fraction.

G.25.4 Emissions of CH_4

It has not been possible to find high quality data about the CH_4 emissions occurring during the storage of degassed liquid fraction. Yet, in the latest Danish national inventory report for greenhouse gases, Nielsen et al. (2009)

calculated the absolute CH_4 reduction of biogas-treated slurry by using the IPCC methodology[21], coupled with a reduction potential of 30 % in the case of cow slurry. When applying this equation, Nielsen et al. (2009) considered the VS content of the treated slurry instead of the VS content ex-animal.

This is the methodology that will be applied in this project. The VS of the liquid fraction is estimated as 80% of the DM content. This corresponds to a VS content of 44.66 kg per 1000 kg liquid fraction.

The CH_4 emissions are therefore calculated as: 44.66 kg VS/1000 kg degassed liquid fraction * 0.24 m^3 CH_4/kg VS * 0.67 kg CH_4/m^3 CH_4 * 10% * (100-30) % = 0.503 kg CH_4/1000 kg degassed liquid fraction.

G.25.5 Emissions of CO_2

Emissions of CO_2 were estimated with the calculated ratio between emissions of CO_2 and CH_4 in anaerobic conditions, i.e. 1.67 kg CO_2 per kg CH_4 (see section G.5.5). As mentioned in section G.2, part of the produced CO_2 from the outdoor storage is emitted to air immediately and part of the CO_2 is dissolved in the slurry. However, in this life cycle assessment, it is calculated as all the CO_2 is emitted to air immediately, which makes the interpretation of the sources easier, as detailed in section G.2.

G.25.6 Emissions of NH_3

Hansen et al. (2008) states that there are no clear differences between the ammonia (NH_3) emissions from degassed slurry and untreated slurry. On one hand, the lower content of dry matter might reduce the emission of ammonia, on the other hand, TAN concentration and pH of degassed slurry are higher, which both increase the potential for ammonia emissions. Yet, Sommer (1997), who measured the NH_3 volatilization from both covered (one tank covered by straw and one tank covered by clay granules) and uncovered storage tank containing digested slurry, concluded that ammonia volatilization from the covered slurry was insignificant.

The ammonia emissions occurring during the storage of the degassed liquid fraction are therefore calculated using the same assumptions as for the reference scenario, i.e. the emission of NH_3–N are 2% of the total-N, based on Poulsen et al. (2001). The total N being 7.98 kg N/1000 kg degassed liquid fraction, the NH_3-N emissions are 0.160 kg NH_3-N per 1000 kg degassed liquid fraction.

G.25.7 Emissions of N_2O, NO-N and N_2-N

In the reference scenario, the direct N_2O emissions for storage were based on IPCC guidelines (IPCC, 2006). However, the IPCC methodology does not provide any emission factor for storage of degassed liquid fraction. The fact that the liquid fraction is degassed involves a reduction in the N_2Oemissions,

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[21] According to IPCC (2006), the methane emission can be calculated as:
CH_4 [kg] = VS [kg] * B_0 * 0.67 [kg CH_4 per m^3 CH_4] * MCF
B_0 = 0.24 m^3 CH_4 per kg VS for dairy cows (IPCC, 2006, Table 10A-7). The MCF value used is 10 % (for liquid slurry with natural crust cover, cool climate, in table 10-17 of IPCC (2006)). This is also the MCF recommended under Danish conditions by Nielsen et al. (2009).

as part of the most easily converted dry matter was removed during the biogas production (Mikkelsen et al., 2006).

Yet, as for the CH_4 emissions, the latest Danish national inventory report for greenhouse gases (Nielsen et al., 2009) considered a reduction potential factor for estimating the reductions in N_2O-N emissions obtained when the slurry is biogas-treated. In the case of cow slurry, this reduction potential is 36% (Nielsen et al., 2009).

In the present section, the direct N_2O-N emissions will be estimated as in section G.5.7 (i.e. relatively to the emissions in the reference scenario but adjusted with the different N content), and this result will be multiplied by (100-36) % in order to consider the fact that the liquid fraction is degassed.

The direct N_2O-N emissions are therefore calculated as: 0.034 kg N_2O-N/1000 kg slurry ex-housing * (7.98 kg N in 1000 kg of degassed liquid fraction/ 6.34 kg N in 1000 kg slurry ex-housing) * (100-36) % = 0.0274 kg N_2O-N/1000 kg degassed liquid fraction.

The NO-N and N_2-N emissions were calculated in the same way as in Annex A, i.e. based on the study of Dämmgen and Hutchings (2008). In their study, they assumed that the emission of nitrogen monoxide (NO) is the same as the direct emission of nitrous oxide (N_2O) (measured as NO-N and N_2O-N). Furthermore, they assumed that emission of nitrogen (N_2) is three times as high as the direct emissions of nitrous oxide (N_2O) (measured as N_2-N and N_2O-N).

As regarding the total NO_x emissions ($NO_x = NO + NO_2$), it was assumed, as in Annex A, that $NO_x = NO$. This is because it has not been possible to find data on NO_2.

Therefore, this means that the NO-N emissions (and thereby the NO_x-N emissions) correspond to 0.0274 kg N_2O-N per 1000 kg degassed liquid fraction, and the N_2-N emissions correspond to 0.0822 kg per 1000 kg degassed liquid fraction.

The indirect N_2O-N emissions can be calculated as described by IPCC guidelines (IPCC, 2006), i.e. as 0.01 * (NH_3-N + NO_x-N). This gives indirect N_2O-N emissions of 0.0019 kg per 1000 kg degassed liquid fraction.

G.25.8 Life cycle data and mass balances for storage of liquid fraction

Table G.33 summarizes the LCA data for the storage of the degassed liquid fraction and presents the comparison with the storage emissions in Annex A. It must be emphasized that 1000 kg of degassed liquid fraction do ***not*** correspond to 1000 kg slurry ex-animal, so the values of Annex A versus Annex G are not directly comparable. Values from Annex A were only included since they were needed for the calculation of some of the emissions. Table G.34 presents the mass balances of the degassed slurry in order to establish its composition after the storage.

In this table, it can be noticed that the change of DM is estimated as the losses of N and C. As explained in section G.5.8, it is acknowledged that this is a rough estimation, as other elements of greater molecular weight may also be lost (e.g. dissolved O_2). The estimated DM change shall therefore be seen as a minimum change, the actual DM change may in fact be greater than the one taken into account in this study.

Table G.33
Life cycle data for storage of the degassed liquid fraction. All data per 1000 kg of degassed liquid fraction “ex-separation”.

	Reference cow slurry (scenario A)	Degassed liquid fraction (dairy cow slurry) (scenario G)	Comments
Input			
Degassed liquid fraction “ex-separation”		1000 kg	The emissions are calculated relative to this.
Slurry “ex-housing”	1000 kg		
Water	44 kg	44 kg	
Concrete slurry store	Included	Included	As in scenario A.
Cut straw	2.5 kg	2.5 kg	As straw is regarded as a waste product from cereal production (rather than a co-product), the life cycle data of straw production is not included.
Output			
Slurry/degassed liquid fraction “ex-storage”	1044 kg	1044 kg	
Energy consumption			
Electricity		1.45 kWh	Electricity for pumping and stirring, see text.
Emissions to air			
Carbon dioxide (CO_2)	4.21 kg (if calculated as in Annex G :2.81 kg)	0.840 kg	Estimation based on the ratio between CH_4 and CO_2 emissions, i.e. CO_2 = 1.67 * emissions of CH_4
Methane (CH_4)	1.68 kg	0.503 kg	IPCC methodology with the VS content in the liquid fraction, and with a reduction of 50 % (see text): (55.83 kg DM *80 %) kg VS/1000 kg liquid fraction * 0.24 m^3 CH_4/kg VS * 0.67 kg CH_4/m^3 CH_4 * 10% * (100-30) % = 0.503 kg CH_4/1000 kg liquid fraction.
Ammonia (NH_3-N)	0.13 kg	0.160 kg	NH_3-N = 2% of the total-N in the degassed liquid fraction “ex-separation”, see text.
Direct emissions of Nitrous oxide (N_2O-N)	0.034 kg	0.0274 kg	Estimation based on the emissions in the reference scenario, but adjusted with the relative N content. A reduction of 36 % was considered (see text): 0.034 kg N_2O-N * (7.98 kg N in degassed liquid fraction/ 6.34 kg N in slurry ex-housing) * (100-36) % = 0.0274 kg N_2O-N/1000 kg degassed liquid fraction.
Indirect emissions of Nitrous oxide (N_2O-N)	0.0016 kg	0.0019 kg	0.01 kg N_2O–N per kg (NH_3–N + NO_X–N) volatilised (IPCC, 2006, table 11.3), see text.
Nitrogen monoxide (NO-N) (representing total NO_X)	0.034 kg	0.0274 kg	Estimate based on Dämmgen and Hutchings (2008), consisting of assuming that NO-N = (direct) N_2O-N * 1, see text.
Nitrogen dioxide (NO_2-N)	No data	No data	No data
Nitrogen (N_2-N)	0.10 kg	0.0822 kg	Estimate based on Dämmgen and Hutchings (2008), consisting of assuming that N_2-N = (direct) N_2O-N * 3.
Discharges to soil and water			
	None	None	Assumed to be none, as leakages from slurry tanks are prohibited in Denmark

Table G.34.
Mass balances for storage of degassed liquid fraction

	Composition of degassed liquid fraction AFTER separation and BEFORE storage (from table G.27) [kg per 1000 kg degassed liquid fraction]	Mass balance: Change during storage of degassed liquid fraction [kg]	Mass balance: Amount after storage of degassed liquid fraction [kg]	Composition of degassed liquid fraction AFTER storage [kg per 1000 kg degassed liquid fraction AFTER storage]
Total mass	1000 kg	44 kg	1044 kg	1000 kg
Dry matter (DM)	55.83 kg	- 0.903 kg c)	54.93 kg	52.61 kg
Total-N	7.98 kg	- 0.297 kg a)	7.68 kg	7.36 kg
Total-P	0.62 kg	No change	0.62 kg	0.59 kg
Potassium (K)	6.98 kg	No change	6.98 kg	6.69 kg
Carbon (C)	23.69 kg	- 0.606 kg b)	23.08 kg	22.11 kg
Copper (Cu)	0.014 kg	No change	0.014 kg	0.013 kg
Zinc (Zn)	0.0213 kg	No change	0.0213 kg	0.0204 kg

[a] Changes in total N: 0.160 kg NH_3-N + 0.0274 kg N_2O-N + 0.0274 kg NO-N + 0.0822 kg N_2-N = 0.297 kg N

[b] Changes in total C: 0.840 kg CO2 * 12.011 [g/mol] /44.01 [g/mol] + 0.503 kg CH4 * 12.011 [g/mol] /16.04 [g/mol] = 0.606 kg C

[c] The change in DM is assumed to be identical to the sum of the loss of N and C

G.26 Transport of degassed liquid fraction to field

The transport of the degassed liquid fraction to the field is identical to the process described in section G.6 (transport of the liquid fraction to the field).

This means that the process “Transport, tractor and trailer” from the Ecoinvent database has been used (Nemecek and Kägi, 2007, p.204), for a distance of 10 km. This includes the construction of the tractor and the trailer.

G.27 Field processes for degassed liquid fraction

G.27.1 General description

As in the process described in section G.7 (field processes for [non-degassed] liquid fraction), the data from the Ecoinvent process “Slurry spreading, by vacuum tanker” (Nemecek and Kägi, 2007, p. 198) were used for the emissions related to spreading equipment “consumption”. This includes the construction of the tractor and the slurry tanker, as well as the diesel consumption. The diesel consumption due to the use of the “tanker” in the Ecoinvent process was adjusted to 0.4 litres of diesel per 1000 kg of slurry, based on Kjelddal (2009) (the same as in Annex A).

G.27.2 Emission of CH_4 and CO_2

The CH_4 emissions on the field are assumed to be negligible, as the formation of CH_4 requires an anaerobic environment, which is, under normal conditions, not the case in the top soil.

CO_2 emissions and C-binding in the soil are modelled by the dynamic soil organic matter model C-TOOL (Petersen et al., 2002; Gyldenkærne et al., 2007). The development in organic soil N is modelled by assuming a 10:1 ratio in the C to N development.

G.27.3 Emissions of NH_3

For the ammonia emissions occurring as a result of the fertilisation operations, no data were found in the literature for the specific case of the degassed liquid fraction. Yet, some data are available for degassed slurry (as compared to raw slurry) and for the (non-degassed) liquid fraction (as compared to raw slurry).

According to Hansen et al. (2008), there are no clear difference between the emissions from degassed slurry and untreated slurry since degassed slurry presents both factor promoting and inhibiting NH_3 volatilization. However, one of the main conclusion in a recent study by Möller and Stinner (2009) is that factors promoting NH_3 volatilization (higher amounts of NH_4-N and higher pH) predominate over the factors reducing the propensity for volatilization (lower viscosity, lower dry matter content). Different studies also report measurements showing that digested manure is more likely to lose ammonia than untreated manure after surface application (Bernal and Kirchmann, 1992; Sommer et al., 2006; Amon et al., 2006). Bernal and Kirchmann (1992) measured NH_3-N losses of 14 % of the total applied N over a 9 days period from anaerobically treated pig manure mixed with soil. In Sommer et al. (2006), accumulated NH_3 volatilization after 96 h were increased of about 27.3 % on a sandy loam soil and of approximately 21.6 % on a sandy soil (for digested manure as compare to undigested manure). During the field application of digested cow slurry, Amon et al. (2006) measured NH_3 emissions of 220.0 g NH_3 per m^3 digested slurry. Assuming a density of 1000 kg/m^3 for the digested slurry, this corresponds to 0.220 kg NH_3 per 1000 kg digested slurry. Börjesson and Berglund (2007) assumed an average increase of 24 % of the NH_3 emissions when digested manure is applied as compared to undigested manure (i.e. from 250 to 310 g NH_3 per tonne of manure).

As regarding the effect of the separation, a reduction of 50 % of the ammonia volatilization can be expected from a liquid fraction, as compared to raw slurry (see section G.7).

Since the liquid degassed fraction is subjected to both increasing and reducing factors as regarding the ammonia emission potential, and since no data were found specifically for this, the ammonia emissions were calculated as in the reference scenario. This is exactly as described in section G.7, but without the 50 % reduction factor in the case of the emissions occurring after application.

G.27.4 Emissions of N_2O and NO_X-N

The direct N_2O emissions are generally assumed to be smaller for degassed slurry than for untreated slurry (Sommer et al. 2001). This is because digested manure contains less easily decomposed organic matter than undigested manure (Börjesson and Berglund, 2007) and because more N is in a form already available to the plants (NH_4^+). This means that less N shall be available to microorganisms for nitrification (where NO_3^- is formed), and thus, the potential for denitrification (where NO_3^- is reduced to N_2O, and subsequently to N_2) is also reduced. This is also in accordance with Marcato et al. (2009), who concluded from their results that there are fewer risks for oxygen competition between the crops and soil bacteria (and therefore of N_2O emissions) with digested slurry as compared to undigested slurry. According to Sommer et al. (2001, table 2) N_2O emissions with degassed slurry are in the magnitude of 0.4 % of the applied N. Based on Sommer et al. (2001), Nielsen (2002) used, for field emissions with digested slurry, a reduction corresponding to 41 % of the emissions with raw slurry (i.e. from 34 to 20 g N_2O/ton manure) and Börjesson and Berglund (2007) assumed a reduction of 37.5 % (i.e. from 40 to 25 g N_2O per tonne of manure).

In this project, no specific data as regarding the direct N_2O emissions related to the use of the degassed liquid fraction were found. Therefore, the estimate of Sommer et al. (2001) for digested (but non-separated) slurry will be used as the best available data (i.e. 0.4 % of the applied N). This should be regarded as a rather rough estimate. It may also overestimate the N_2O emissions, as the slurry is both degassed and separated, which reduced significantly its content in organic N. In fact, according to Møller et al. (2007b), the centrifugal separation mainly transfers the organic N to the solid fraction, while the dissolved NH_4^+ goes in the liquid fraction.

As in section G.7, indirect N_2O emissions ***due to ammonia and NO$_X$*** are evaluated as 0.01 kg N_2O-N per kg of (NH_3 + NO_X) volatilized. The indirect N_2O-N emissions ***due to nitrate leaching*** correspond to 0.0075 kg N_2O-N per kg of N leaching. The emissions of NO_X-N are calculated as 0.1* direct N_2O-N, based on Nemecek and Kägi (2007).

G.27.5 Emissions of N_2-N

The N_2-N emissions are based on the estimates from SimDen (Vinther, 2004). For soil type JB3 the N_2-N:N_2O-N ratio is 3:1 and for soil type JB6 the N_2-N:N_2O-N ratio is 6:1.

G.27.6 Calculation of degassed liquid fraction fertilizer value

The fertilizer value for degassed liquid fraction is calculated and detailed in section G.28.

G.27.7 Nitrate leaching

The approach from section G.7.6 is utilized, where the liquid fraction is equaled by a proportion of cattle slurry, and an additional amount of mineral N. The C:N proportion is 45.2 [kg C] / (5.79-0.02-0.73) [kg N] = 8.97 for the cow slurry and 22.11 [kg C] / (7.36-0.02-0.905) [kg N] = 3.44 for the liquid fraction. The “virtual” proportion of N assumed to affect the soil and plants as cattle slurry is therefore 3.44/8.97 = 0.383, and the virtual proportion of N assumed to affect the soil and plants as mineral N is accordingly 0.616.

G.27.8 Phosphorus leaching

For P leaching, the same assumptions as those used in Annex A were used, i.e., 10% of the P applied to field has the possibility of leaching and 6% of this actually reach the aquatic recipients, based on Hauschild and Potting (2005).

G.27.9 Cu and Zn fate

As in Annex A, it is considered that the entirety of the Cu and Zn applied will leach through the water compartment.

G.27.10 Life cycle data for field application of degassed ex-storage liquid fraction

Table G.35 presents the life cycle data for the application of degassed ex-storage liquid fraction on the field. The results of the reference case (Annex A) are also presented for comparison purposes. However, in order to be comparable, both results must be related to the functional unit, i.e. 1000 kg slurry ex-animal.

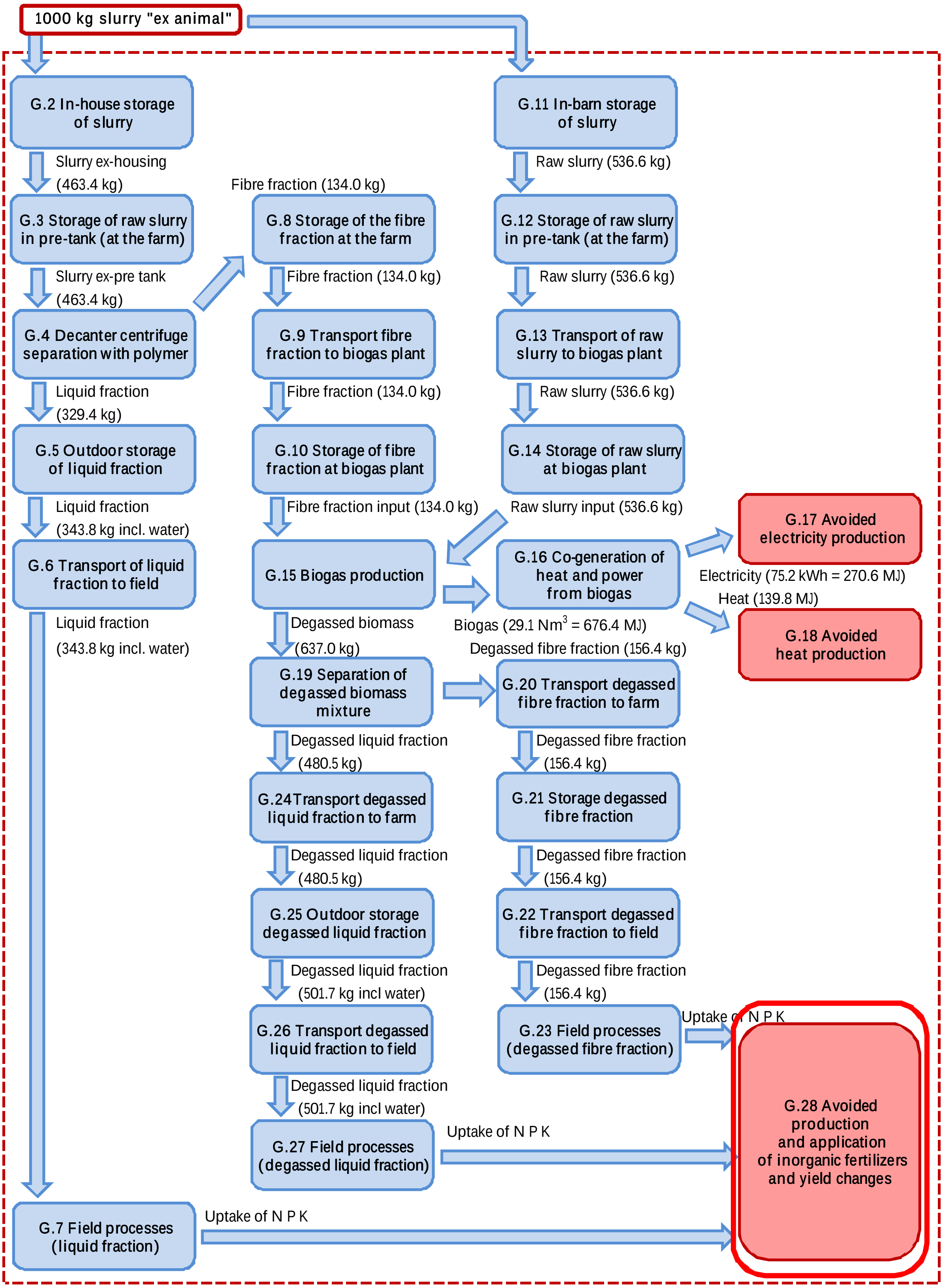
Table G.35.
Life cycle data for application of degassed liquid fraction and field processes. All data per 1000 kg of “degassed liquid fraction ex-outdoor storage”.

	Dairy cow slurry (Annex A)	Degassed liquid fraction ex-storage (Annex G)	Comments
Input			
Slurry/ degassed liquid fraction “ex-storage”	1000 kg	1000 kg	Slurry / degassed liquid fraction from the outdoor storage. This is the reference amount of slurry, i.e. the emissions are calculated relative to this.
Output			
Slurry on field, fertiliser value	Fertiliser replacement value: 4.21 kg N 0.98 kg P 5.65 kg K	Fertiliser replacement value (N, P and K): See section G.28	
Energy consumption			
Diesel for slurry	0.4 litres of diesel	0.4 litres of diesel	See text.
Emissions to air			
Carbon dioxide (CO_2) Soil JB3 Soil JB6	 126.4 kg (154.5 kg) 124.2 kg (153.8 kg)	 47.9 (71.6) kg 46.8 (71.3) kg	Modelled by C-TOOL (Gyldenkærne et al, 2007). 10 year value shown, 100 years value in parenthesis.
Methane (CH_4)	Negligible	Negligible	The CH_4 emission on the field are assumed to be negligible, as the formation of CH_4 requires anoxic environment (the field is aerobic) (Sherlock et al., 2002).
Ammonia (NH_3-N) during application	0.02 kg	0.021 kg	NH3 emissions during application: 0.5% of NH4+-N “ex-storage”, the NH4+-N “ex-storage” being evaluated as 58 % of total N. 7.36 kg N * 58% * 0.5% = 0.021 kg NH_3-N
Ammonia (NH_3-N) in period after application	0.73 kg	0.905 kg	Correspond to 0.217 kg NH_3-N per kg NH_4^+-N in the degassed liquid fraction (including NH_3-N during application), and NH_4-N is here evaluated as 58 % of total N. (0.217 kg NH_3-N/kg TAN-N * 58% * 7.36 kg N) – 0.021 kg NH_3-N during application = 0.905 kg NH_3-N
Direct emissions of Nitrous oxide (N_2O-N)	0.06 kg [0.018-0.18]	0.029 kg	0.4 % of the applied N, based on Sommer et al. (2001), see text.
Indirect emissions of Nitrous oxide (N_2O-N) Soil JB3 Soil JB6	0.006 kg 0.016 kg (0.019 kg) 0.0125 kg (0.015 kg)	0.009 kg 0.022 kg (0.025 kg) 0.017 kg (0.020 kg)	Indirect emissions due to emissions of ammonia and NO_X: 0.01 kg N_2O–N per kg (NH_3–N + NO_X–N) volatilised (IPCC, 2006). Indirect emissions due to nitrate leaching: 0.0075 kg N_2O–N per kg N leaching (IPCC, 2006).
Nitrogen oxides (NO_x-N)	0.006 kg	0.0029 kg	NO_X–N = 0.1 * N_2O-N according to Nemecek and Kägi (2007)

Table G.35. (Continuation)
Life cycle data for application of degassed liquid fraction and field processes. All data per 1000 kg of “degassed liquid fraction ex-outdoor storage”.

	Dairy cow slurry	Degassed liquid fraction ex-storage	Comments
Emissions to air			
Nitrogen (N_2-N) Soil JB3 Soil JB6	 0.18 kg 0.36 kg	 0.087 kg 0.174 kg	Estimated from the SimDen model ratios between N_2-N and N_2O-N (see text): 3:1 for soil JB3 and 6:1 for soil JB6.
Discharges to soil			
Nitrate leaching Soil JB3 Soil JB6	 2.16 (2.59) kg N 1.67 (2.04) kg N	 2.91 (3.35) kg N 2.25 (2.62) kg N	See text
Phosphate leaching	0.098 kg P	0.059 kg P	10% of the P applied to field has the potential to leach
Copper (Cu)	0.0116 kg	0.013 kg	See table G.34.
Zinc (Zn)	0.0224 kg	0.0204 kg	See table G.34.

Process G.28: Avoided production and application of mineral fertilizers and yield changes



G.28 Avoided production and application of mineral fertilizers

G.28.1 General description

In this scenario, nitrogen is spread to the field at 3 points: Via the liquid fraction (section G.7), via the degassed fibre fraction (section G.23) and via the degassed liquid fraction (section G.27).

Before continuing this section, it is very important to clarify the difference between "The fertiliser value" and "The replaced amount of mineral fertiliser":

- ***The agronomic fertiliser value*** regards the nutritional value for the plants. It is estimated on the basis of the N amount, origin (pig, cattle) and content of organic matter in the slurry. This is used for calculating the yield increase. An increase in the crop production occurs if the agronomic fertiliser value of organic fertilisers applied in scenario G (all together for the total system) is higher than the fertiliser value for the reference scenario A, and vice versa. The calculations regarding the agronomic fertiliser value aim at representing the behaviour of the biophysical system.

- ***The replaced amount of mineral fertiliser*** is the amount of mineral fertiliser that the farmer is not allowed to bring out to the field, due to spreading the slurry (i.e. the substituted amount of mineral fertiliser). These calculations are based on Danish laws as well as on what the farmers actually do in practice. It has not a one-to-one relation to the net mineralisation in the growing season caused by the animal slurry, so it may differ from "real plant availability".

The agronomic fertiliser value and ***the replaced amount of mineral fertiliser*** are hence two different things, and in consequence they may also differ numerically.

The calculations of the replaced amount of mineral fertiliser (based on Danish law) are explained in section G.28.2. The agronomic fertiliser value and the yield changes are explained in section G.28.3.

G.28.2 Calculation of the replaced amount of mineral fertiliser

As explained in Annex F, the starting point for calculating the replaced amount of mineral fertiliser is the Danish law and the guidelines for this (Gødskningsloven (2006), Gødskningsbekendtgørelsen (2008), and Plantedirektoratet (2008b)).

The foundation for the law is that there is a "quota" of nitrogen for each field, depending on the crop and soil type [22]. In addition to this, there is an

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[22] Gødskningsbekendtgørelsen (2008), chapter 3, paragraph 3 and 4:
"Stk. 3. En marks kvælstofkvote opgøres på grundlag af den eller de afgrøder, der dyrkes på arealet, dog på grundlag af den senest etablerede afgrøde, hvis arealet er sået om, fordi afgrøden er slået fejl."

upper limit for how much of the "nitrogen quota" that can be applied as animal slurry.

When applying cattle slurry, the N in the slurry replace 70% mineral fertiliser, which means that if applying 100 kg N in slurry, the farmer has to apply 70 kg mineral N fertiliser ***less*** (Gødskningsbekendtgørelsen (2008), paragraph 21). For example, if the farmer has a field with winter barley, and the soil type is JB3, the farmer has a "Nitrogen quota" for that field at 149 kg N per ha (Plantedirektoratet, 2008). If the farmer applies 100 kg N per ha as dairy cow slurry, this accounts for 70 kg N per ha, which means that the farmer is allowed to apply the remaining 149 kg N per ha – 70 kg N per ha = 79 kg N per ha as mineral N fertiliser.

However, for separated slurry and for degassed slurry, the rules are not as straightforward.

For separated slurry, the "mineral fertiliser replacement values" of the separated fractions is set by the producer (i.e. the farmer or the biogas plant that separate the slurry). However, they have to follow the rule of conservation:

a) The sum of the "mineral fertiliser replacement value" of the **outgoing** fractions shall be the same as the "mineral fertiliser replacement value" of the **ingoing** slurry before separation[23].

For degassed biomass from biogas plants, there are three rules that can be applied, and the biogas plant can choose which one to apply[24]:

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[23] Gødskningsbekendtgørelsen (2008), paragraph 20:
§ 20. For det enkelte forarbejdningsanlæg gælder, at den totale mængde kvælstof i den forarbejdede husdyrgødning skal svare til den indgående totale mængde kvælstof. Ligeledes skal den andel, der skal udnyttes, af den totale mængde kvælstof i forarbejdet husdyrgødning mindst svare til andelen, der skal udnyttes, af den indgående totale mængde kvælstof […].
Stk. 2. Producenter af forarbejdet husdyrgødning fastsætter ved salg eller afgivelse til en virksomhed registreret efter lovens § 2 det totale antal kg kvælstof i gødningen og den andel af det totale antal kg kvælstof, der skal udnyttes.

[24] Gødskningsbekendtgørelsen (2008), paragraph 19: § 19. Indholdet af kvælstof i afgasset biomasse skal beregnes på grundlag af oplysninger om den mængde kvælstof i husdyrgødning, der er ***tilført*** biogasanlægget samt oplysninger om den mængde kvælstof i anden organisk gødning, der er tilført biogasanlægget, jf. § 22, stk. 6. Alternativt kan biogasanlæg, der leverer afgasset biomasse til virksomheder omfattet af lovens § 2 eller til andre virksomheder med henblik på endelig brug i virksomheder omfattet af lovens § 2, ***få indholdet af kvælstof i afgasset biomasse bestemt ved analyse*** af repræsentative prøver foretaget mindst en gang inden for perioden 1. august til 31. juli i den planperiode, gødningen skal anvendes, jf. stk. 2. Biogasanlægget skal opgøre den leverede mængde afgasset biomasse, som analysen gælder for. Stk. 2. Analyse af indhold af kvælstof i gødning skal foretages af et laboratorium, der er autoriseret hertil af Plantedirektoratet […].

Plantedirektoratet (2008b): Udnyttelsesprocenten beregner producenten (ud fra ***indgangsmaterialet*** eller analyse af repræsentative prøver). For afgasset gylle kan udnyttelsesprocenten i stedet sættes som andelen for svinegylle, der i 2007/08 er 75 pct.

b) The “mineral fertiliser replacement value” of the **outgoing** biomass is calculated in accordance with the **ingoing** biomass (“rule of conservation”).

c) The producer of the degassed biomass (i.e. the biogas plant staff) sets the “mineral fertiliser replacement value” for the degassed biomass based on representative measurement of samples of the degassed biomass.

d) Or, the “mineral fertiliser replacement value” for the degassed biomass can be set to 75% as for pig slurry.

In the following, calculations have been performed for some of the rules mentioned above.

When following rule a) + b) strictly, the “mineral fertiliser replacement value” is calculated as follows:
The replaced amount of mineral N fertiliser for Annex F is based on 4 steps:

- Step 1: Use a substitution value of 50% for the fibre fraction of slurry.
- Step 2: Acknowledging the above, make the weighted sum of the substitution values (liquid and fibre), i.e. 70 % for cattle and 75 % for pig.
- Step 3: Make a weighed sum of the substitution values for the materials entering the biogas plant – this is the substitution value for the end product before separation.
- Step 4: Use a substitution value of 50% for the fibre fraction of the degassed material from the biogas plant, and put “the rest” upon the liquid fraction (much like step 1 and 2).

The calculations for scenario F are shown in table G.36.

Table G.36.
Replaced amount of mineral N fertiliser in Annex G. All calculations per 1000 kg slurry ex-animal

Calculations
Step 1: Substitution value for fibre fraction to biogas plant Amount of fibre fraction: 133.995 kg (see figure G.1). N in fibre fraction: 10.96 kg per 1000 kg fibre fraction (see table G.6). Substitution value: 50% of 10.96 kg per 1000 kg fibre fraction * 133.995 kg fibre fraction / 1000 kg = 0.73429 kg N per 1000 kg slurry ex-animal. This is the substitution value that “belongs” to the fibre fraction that is sent to the biogas plant. This is “input” to the biogas plant.
Step 2: Acknowledging the above, make the weighted sum of the substitution values (liquid and fibre). For raw cattle slurry, the substitution value is 70 %. Here rule (a) applies: “The sum of the “mineral fertiliser replacement value” of the outgoing fractions shall be the same as the “mineral fertiliser replacement value” of the ingoing slurry before separation”. The mineral fertiliser replacement value of untreated, raw dairy cow slurry is calculated based on the Danish Norm Data (DJF, 2008), which was also done in Annex A (section A.6.1). From the Danish Norm Data tables, the farmer knows the value of 6.02 kg N per kg slurry ex storage (see also table A.6 and A.2). The Danish Norm Data is what the farmer use for the accounts[1]: 6.02 kg N per 1000 kg slurry ex storage (table A. 2). However, there is only 463.347 kg slurry being separated (see figure G.1). For the system, the mineral fertiliser substitution value is then: 6.02 kg N per 1000 kg slurry ex storage * 1044 kg slurry ex storage / 1000 kg slurry ex animal * 70% = 4.3994 kg N per 1000 kg slurry ex-animal. However, there is only 463.347 kg slurry being separated (see figure F.1), i.e. 4.3994 kg/1000 kg * 463.347 kg = 2.03846 kg N. • Of this 2.03846 kg N, 0.73429 kg N belongs to the fibre fraction (as calculated in step 1). • The difference i.e.: 2.03846 kg N – 0.73429 kg N = 1.30417 kg N belongs to the liquid fraction. Mineral fertiliser replacement value for the liquid fraction (at the farm): **1.30417 kg N**
Step 3: Make a weighed sum of the substitution values for the materials entering the biogas plant. Rule (b): “Mass balance in and out of Biogas Plant – i.e. the “mineral fertiliser replacement value” of the outgoing biomass is calculated in accordance with the ingoing biomass”. • The raw slurry going directly to biogas plant (without separation) has a mineral fertiliser replacement value of 4.3994 kg N per 1000 kg slurry (as described under step 2 above – 70% of 6.02 kg N ex storage). The amount of this raw slurry is 536.653 kg (see figure G.1). Its mineral fertiliser replacement value is: 4.3994 kg N per 1000 kg slurry * 536.653 kg slurry/1000 kg = 2.36095 kg N per 1000 kg slurry ex-animal. This is the substitution value for the raw slurry into the biogas plant. • At the plant, a biomass mixture is made from this raw slurry and the fibre fraction from step 1, so the substitution value for this input mixture is: 0.73429 kg N (fibre fraction, step 1) + 2.36095 kg N (raw slurry, see above) = 3.09524 kg N. This is the substitution value for the input biomass mixture going into the biogas plant, and accordingly also the substitution value for the degassed biomass mixture coming out of the biogas plant – i.e. the degassed biomass before separation. This value is used for the further calculations.
Step 4a: Use a substitution value of 50% for the fibre fraction of the degassed material from the biogas plant (like step 1) Amount of degassed fibre fraction: 156.443 kg (see figure G.1). N in fibre fraction: 6.60 kg per 1000 kg fibre fraction (see table G.27). Substitution value: 50% of 6.60 kg per 1000 kg fibre fraction * 156.443 kg fibre fraction / 1000 kg = 0.51626 kg N Mineral fertiliser replacement value the degassed fibre fraction: **0.51626 kg N**
Step 4b: Calculation of the substitution value for the liquid fraction as “the rest”. Here, rule (a) applies again: “The sum of the “mineral fertiliser replacement value” of the outgoing fractions shall be the same as the “mineral fertiliser replacement value” of the ingoing slurry before separation”. • Total substitution value out of biogas plant = total substitution value in biogas plant, as calculated in step 3: 3.09524 kg N. • Substitution value for the liquid fraction = total from biogas plant – fibre fraction (from step 4a) = 3.09524 kg N - 0.51626 kg N = 2.57898 kg N Mineral fertiliser replacement value for the degassed liquid fraction (after the biogas plant: **2.57898 kg N**
Total amount of substituted mineral N fertiliser in the system 1.30417 kg N + 0.51626 kg N + 2.57898 kg N = **4.3994 kg N**

[1] It should be noted, that it might be more logical to use “ex housing data” for separation, but the farmers do not have information from the Norm Data on these. Furthermore, it can be argued that the loss of N during the outdoor storage is relatively low (2% according to the Norm Data), accordingly, it does not make a big difference

whether the calculations are based on “ex housing” data or “ex storage” data. Accordingly, the N substitution value of the untreated slurry (before separation) is based on the Danish Norm Data (DJF, 2008).

Note that this 4.3994 kg N is identical to 70% of the initial 6.02 kg N per 1000 kg slurry ex storage * 1044 kg slurry ex storage per 1000 kg slurry ex animal. This is logical, as this is the amount that is “divided” into the different fractions when applying rule (a) and rule (b) which both conserve the masses.

It should also be noted, that this amount is identical to the amount of substituted mineral N fertiliser for the reference system in Annex A.

As this study is a comparison, the calculations of the replaced amount of mineral N fertiliser are shown in table G.37, based on the explanations in Annex A, section A.6.1.

Table G.37.
Replaced amount of mineral N fertiliser in scenario A

Fraction	Calculations	Replaced amount of mineral N fertiliser [kg N per 1000 kg slurry ex animal]
Slurry	Calculations for Annex A, see explanations in section A.6.1: 70% of 6.02 kg N (per 1000 kg slurry ex storage) * 1044 kg slurry ex storage / 1000 kg slurry = 4.3994 kg	4.3994 kg N

G.28.3 Yield changes

The yield changes are calculated as a function of the agronomic fertiliser value in order to determine the “extra amount of N” available for crop uptake. This is translated to a response in extra wheat, as in Annex B of Wesnæs et al. (2009). This means that the production of this extra wheat does not have to be produced somewhere else in Denmark and can consequently be deduced from the system.

The yield change calculations are explained in Annex F, section F.28.3. Utilising the same methods as in section F.28.3[25], the overall N difference between Scenario A and Scenario G is (in kg mineral N equivalent):

0.4663 kg N per 1000 kg slurry ex-animal for soil JB3;
0.4432 kg N per 1000 kg slurry ex-animal for soil JB6.

Accordingly, the extra corresponding wheat is:

For soil JB3: 0.4663 kg N surplus * 9.0 kg extra wheat/kg N surplus = 4.20 kg extra wheat (per 1000 kg slurry ex-animal).

For soil JB6: 0.4432 kg N surplus * 8.1 kg extra wheat/kg N surplus = 3.59 kg extra wheat (per 1000 kg slurry ex-animal).

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[25] The values needed to apply the methodology presented in Annex F can be found in the sections for N leaching, namely G.7.6, G.23.7 and G.27.6.

This same procedure was also applied with the 100 years values for both soil types.

G.28.4 Avoided P and K mineral fertilisers

In this scenario, it is assumed that the degassed fibre fraction is transported to fields with lack of phosphorous. This is in fact the whole purpose of separating the degassed biomass after the biogas plant: To collect the main part of the phosphorous in order to increase the possibilities for using this as fertiliser where P is need (at fields with P deficiency) instead of at the fields close to the pig farm areas where there is surplus phosphorus in the soil (mainly in Jutland).

Accordingly, as the degassed fibre fraction (which contains the main part of the phosphorous) is transported to fields with phosphorous deficiency, it is assumed that 100 % of the phosphorous in this fraction replace mineral P fertiliser.

It is assumed that the same, i.e. 100 % replacement, applies for potassium (K). The actual amount of K substituted may in fact be less than 100 % if the K applied is greater than the crops needs. However, as previous modelisations (e.g. Wesnæs et al., 2009) showed that the avoided K fertilisers have a rather insignificant effect on the overall environmental impacts of slurry management, it is believe that the amount of K avoided (100 % or less) is not likely to affect the results.

The avoided emissions per kg of inorganic N, P and K avoided are modelled as in Annex A, Table A.18.

Annex H. Fibre fraction from mechanical separation for biogas production – Life Cycle Inventory data

H.1 System description

This annex contains Life Cycle Inventory data for biogas production from a mixture of fibre fraction (from mechanically separated slurry from the Samson Bimatech separation process) and raw untreated pig slurry. The biogas is used for co-production of heat and power.

This scenario is set up in order to answer the question: “What are the environmental benefits and disadvantages of using the fibre fraction from Samson Bimatechs mechanical separation of pig slurry (see Annex C) for biogas production compared to the reference scenario for pig slurry?”.

Accordingly, it is different than the scenario in Annex F, where the aim was to analyse an optimised system using “Best Available Technology” for biogas production as far as possible.

The main differences compared to Annex F are:

- The separation technology in this Annex H is based on the Samson Bimatech separation technology.
- Polymer is not added to the separation (polymer is added for the separation in Annex F). It is possible to add this for the Samson Bimatech technology, but data has not been available for this. Adding polymer would give very different results for the separation than the data used in this report.
- The methane conversion rate for the fibre fraction from the Samson Bimatech separation is set to 187 Nm^3 CH_4/ton VS compared to the 319 Nm^3 CH_4/ton VS for the fibre fraction from the mechanical-chemical separation used in Annex F, based on information from Møller (2007).
- Separation after the biogas plant is not included, as this scenario is not set up to be a modelling of “best available technology” and as separation after the biogas plant is not commonly used today. Furthermore, the aim of separating the degassed biomass after the biogas plant is to recover phosphorous, and with that in mind, it would not be profitable to separate a degassed mixture partly originating from a mechanical separation (the one ***before*** the biogas plant) that only separates 9.1% of the phosphorus to the fibre fraction (see table H.2). In this scenario, less than 22% of the phosphorous in the original pig slurry “ex-animal” actually reach the biogas plant [1] and accordingly, it is not the optimal system for phosphorous recovering.

A flow diagram for the scenario for biogas production based on the fibre fraction from mechanically separated slurry and untreated slurry is shown in

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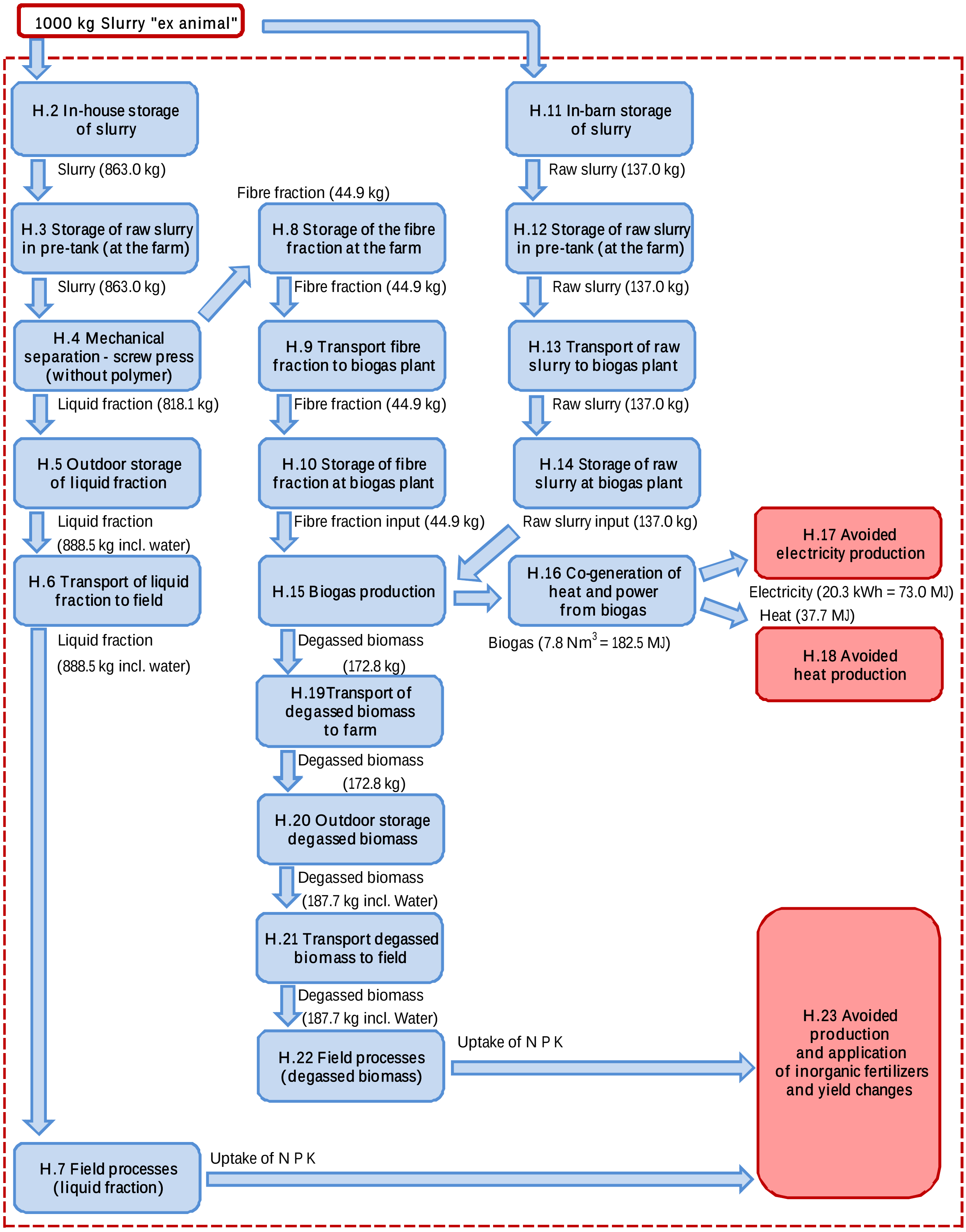
[1] The initial phosphorus content is 1.13 kg P per 1000 kg pig slurry “ex-animal”. From figure H.1, it can be seen that an input of 863 kg pig slurry is separated (H.4), and from this, 818.11 kg ends as liquid fraction. The liquid fraction contains 1.0833 kg P per 1000 kg, i.e. 818.11 kg * 1.0833 kg P per 1000 kg = 0.8863 kg P ends in the liquid fraction. This corresponds to 0.8863 kg P/1.13 kg P*100% = 78.4%, which means that only 21.6% of the P ends at the biogas plant in this system. Therefore only 21.6% of the initial P has the potential to be found in the degassed biomass from the biogas plant, which is judged not enough to justify a separation post biogas.

figure H.1. The process numbers in figure H.1 follows the numbers of the sections in this annex.

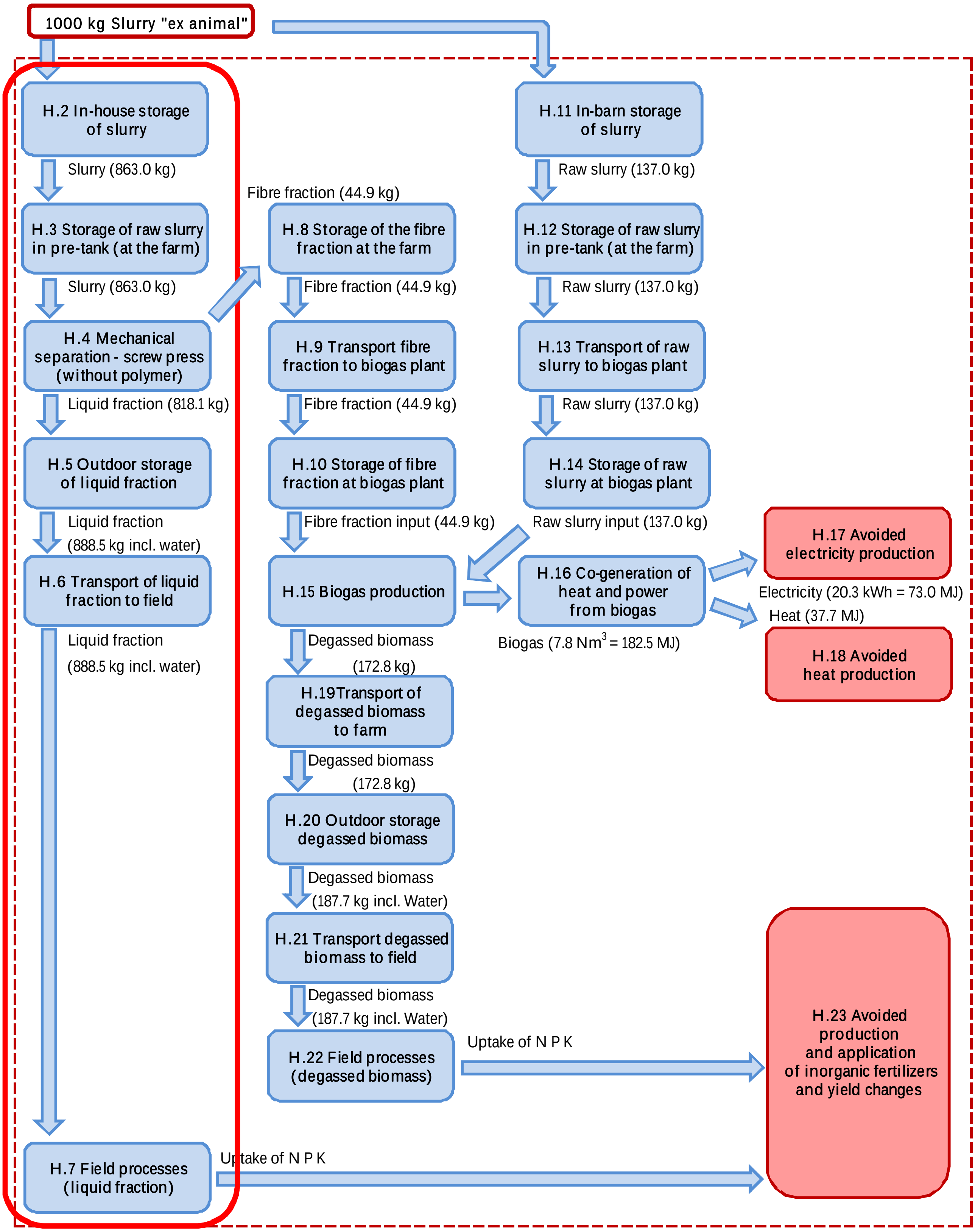
The present annex describes a total of 23 main processes, which were divided into 6 main sections:

- Section 1: Processes H.2 to H.7
  This section focus on the slurry from which the fibre fraction input in the biomass mixture (for biogas) origins. It starts with the raw slurry being produced in the pig barn and stored in the barn (H.2). The slurry is then stored in the pre-tank (H.3) and separated (H.4). This section then continues with the fate of the liquid fraction only. The liquid fraction is stored outdoor (H.5), until it is transported to the field (H.6) and used as a fertilizer (H.7).
- Section 2: Processes H.8 to H.10
  This section is a continuation of the previous, and starts with the fibre fraction output from the separation process (H.4). The fibre fraction is stored on-farm (H.8), transported to the biogas plant (H.9) and temporarily stored at the biogas plant (H.10).
- Section 3: Processes H.11 to H.14
  This section focus on the raw slurry input in the biomass mixture (for biogas). It begins with the raw slurry being produced in the pig barn and stored in the barn (H.11). The slurry is then stored in pre-tank at the farm (H.12), and transported to the biogas plant (H.13). Once at the biogas plant, the raw slurry is stored temporarily (H.14).
- Section 4: Processes H.15 to H.18
  This section focuses on the biogas production (H.15) and the resulting heat and power co-generation (H.16). This co-generation avoids marginal electricity to be produced (H.17) as well as marginal heat (H.18).
- Section 5: Processes H.19 to H.22
  This section focuses on the fate of the degassed biomass. After the biogas plant, it is transported back to the farm (H.19), stored (H.20) until it is transported to the field (H.21) to be used as a fertilizer (H.22).
- Section 6: Process H.23
  Throughout this annex, two organic fertilizers were used: the liquid fraction from the separation (H.7) and the degassed biomass from the biogas plant (H.22). The use of the slurry and degassed biomass as organic fertilizers results in a reduced use and production of inorganic fertilizers (H.23), which is the main focus of this section.

Figure H.1.
Flow diagram for the scenario for biogas production based on fibre fraction from mechanically separated slurry by the Samson Bimatech separation.



Processes H.2 to H.7: Raw slurry from which the fibre fraction origins: production, separation and fate of the liquid fraction



H.2 In-house storage of slurry

In this scenario, the storage of the slurry in the barn has not changed compared to the reference scenario (Annex A). Accordingly, the life cycle inventory data are identical to table A.9 in Annex A. This also means, that the process is identical to the process in Annex F, section F.2 of this report.

The slurry composition when leaving the barn is identical to the slurry "ex-housing" from table A.1 in Annex A. This is shown in table H.1 below.

Table H.1.
Characteristics of slurry "ex-housing" from fattening pigs
Per 1000 kg of slurry ex-housing

	Slurry ex-housing
Total mass	1000 kg slurry ex-housing
Dry matter (DM)	69.7 kg
Ash content	13.2 kg
Volatile solids (VS) Of total VS: - easily degradable - heavy degradable	56.5 kg 34.0 kg 22.5 kg
Total-N (DJF, 2008)	*No data (calculated: 5.54 kg)*
Total-N in this study	5.48 kg
$NH4^+$-N	No data
Total-P	1.13 kg
Potassium (K)	2.85 kg
Carbon (C)	33.3 kg
Copper (Cu)	30.0 g
Zinc (Zn)	89.4 g
Density	1053 kg per m^3
pH	7.8

H.3 Storage of raw slurry in pre-tank at farm

The storage of raw slurry is identical to the process in Annex F, section F.3.

The storage duration is, for this study, assumed to be rather short and it has been assumed that losses of CH_4, CO_2 and N_2O in the pre-tank are negligible.

Accordingly, the composition of the slurry "ex pre-tank" is assumed to be identical to the "ex-housing" composition from table H.1 above.

H.4 mechanical separation (no polymer) – screw press and arc strainers

The mechanical separation process used in this Annex is the Samson Bimatech mechanical separation described in Annex C, section C.4. The life cycle inventory data are shown in table C.4.

Note, that the Samson Bimatech mechanical separation in Annex C does not include the use of polymer. It is possible to add polymer to the separation (J. Mertz, 2008), however this is not included in this report.

The slurry before the separation has the same composition as in Annex C, accordingly, the life cycle inventory data and the resulting separated fibre fraction and liquid fraction are identical to the fractions from Annex C. The composition of the slurry before and after the separation is shown in table H.2 below (and this is identical to table C.3 from Annex C).

Table H.2.
Mass balances for mechanical separation of slurry from **fattening pigs**.
Per 1000 kg of slurry "ex-housing".

	Amount in slurry Ex pre-tank BEFORE separation (values from table H.1)	Separation index (from table C.2, unless otherwise specified)	Mass Balance: Amount transferred to the fibre fraction	Mass balance: Amount transferred to the liquid fraction	Composition of the fibre fraction AFTER separation Fibre fraction * 1000 / 51.98 kg	Composition of liquid fraction AFTER separation Liquid fraction * 1000 kg / 948 kg
	[per 1000 kg ex pre-tank]		[per 1000 kg ex pre-tank]	[per 1000 kg ex pre-tank]	[kg per 1000 kg fiber fraction]	[kg per 1000 kg liquid fraction]
Total mass	1000 kg slurry ex pre-tank	5.198% [a)]	51.98 kg	1000 kg – 51.98 kg = 948.02 kg	1000 kg Fibre fraction	1000 kg liquid fraction
Dry matter (DM)	69.7 kg	29.6%	69.7 kg *29.6% = 20.63 kg	69.7 kg *(100-29.6)% = 49.07 kg	396.9 kg	51.76 kg
Total-N	5.48 kg	6.8%	5.48 kg *6.8% = 0.3726 kg	5.48 kg *(100-6.8)% = 5.1074 kg	7.17 kg	5.387 kg
Total-P	1.13 kg	9.1%	1.13 kg *9.1% = 0.102 kg	1.13 kg *(100-9.1)% = 1.027 kg	1.962 kg	1.0833 kg
Potassium (K)	2.85 kg	2.9%	2.85 kg *2.9% =0.08265 kg	2.85 kg *(100-2.9)% = 2.767 kg	1.59 kg	2.9187 kg
Carbon (C)	33.3 kg	No data Assumed: 29.6%	33.3 kg *29.6% = 9.859 kg	33.3 kg *(100-29.6)% = 23.443 kg	189.67 kg	24.728 kg
Copper (Cu)	30.0 g	4.6%	30.0 g *4.6% = 1.38 g	30.0 g *(100-4.6)% = 28.62 g	26.549 g	30.189 g
Zinc (Zn)	89.4 g	6.3%	89.4 g *6.3% = 5.632 g	89.4 g *(100-6.3)% = 83.768 g	108.35 g	88.361 g
Water content	1000 kg - 69.7 kg = 930.3 kg		31.35 kg [c)]	898.95 kg		

a)The separation index for the mass (3.3%) from table C.2 has not been used as it gave unrealistic results for both the fibre fraction and the liquid fraction. The calculation of the total mass is therefore based on measurements of the fibre fraction, which has a DM of 39.69%. When the DM is 39.69%, and the total DM is 20.63 kg, the total mass is 20.63 kg * 100/39.69 = 51.98 kg. This gives a separation index of (51.98 kg/1000 kg) * 100 % = 5.198 %.

H.5 Outdoor storage of the liquid fraction

H.5.1 General description

The main principles for the outdoor storage of the liquid fraction in this annex are basically the same as for the outdoor storage of the liquid fraction in Annex F, however, as the separation process is different, the composition of the liquid fraction is different. As the emissions depend on the composition of the liquid fraction, the emissions will be different from Annex F (but still be based on the same calculation methods).

As in Annex F, the liquid fraction is stored in an outdoor concrete tank covered with a floating layer consisting of 2.5 kg of straw per 1000 kg slurry stored. Because straw is regarded as a waste product from cereal production (rather than a co-product), the life cycle data of straw production are not included in this study (as in Annex F).

H.5.2 Addition of water

Water will be added in the liquid fraction during storage through precipitations. The amount of precipitations is the same as in Annex A and F, i.e. a total of 86 kg of water.

H.5.3 Electricity consumption

The electricity for pumping and stirring is assumed to be identical to the electricity consumption for the pumping and stirring in Annex F (see section F.5.3), i.e. 1.45 kWh per 1000 kg liquid fraction. This consumption was calculated from the data for raw slurry presented in Annex A, but adjusted by a factor of 0.5 to take into account that the separated liquid fraction is likely to offer much less resistance when stirring or pumping than does the raw slurry. There might be a difference between the viscosity and resistance for the liquid fraction in this annex as compared to the liquid fraction in Annex F since the content of DM is not the same, however, this 0.5 factor adjustment is a rough estimate anyway that only aims to take into account. Moreover, the results of the life cycle assessment for the reference scenario in Annex A shows that the electricity consumption in this stage is rather insignificant for the overall results.

H.5.4 Emissions of CH_4

For the calculation of the emissions of CH_4 from the outdoor storage of the liquid fraction, the same method has been applied as in Annex F, see the explanation in section F.5.4.
As described in section F.5.4, the CH_4 emissions are calculated based on the IPCC methodology, but by using the VS content of the separated liquid fraction (the VS being calculated with the hypothesis that VS = DM * 80 %). This gives a CH_4 emission of 1.248 kg per 1000 kg of liquid separated fraction[2]. When comparing with the values of the CH_4 emission from the outdoor storage of the liquid fraction from Annex F it can be seen that the CH_4 emission from the storage in this annex is significantly higher. This is

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[2] 80 % * 51.76 kg DM per 1000 kg liquid fraction (see table H.2) * 0.45 * 0.67 * 10 % = 1.248 kg

caused by the higher content of DM (and thereby VS) in the liquid fraction. However, it is still a reduction compared to the outdoor storage of the slurry in the reference scenario. The value of 1.248 kg CH_4 per 1000 kg of liquid fraction represents a reduction of 36 % as compared to the emissions occurring during the storage of raw slurry (which was 1.94 kg CH_4 per 1000 kg slurry ex-housing, table A.11, Annex A). This is in the range of values presented by Martinez et al. (2003), where reductions in CH_4 emissions between 7% and 40% were observed from the storage of different mechanically separated liquid fractions, as compared to raw slurry.

H.5.5 Emissions of CO_2

Emissions of CO_2 were estimated as a function of the methane emissions, based on the Buswell equation (Symons and Buswell, 1933) and the composition of pig slurry in terms of organic components constituting the VS. This calculation is detailed in Annex F (section F.5.5) and demonstrates that an amount of 1.42 g of CO_2 is produced per g of CH_4.

As mentioned in section F.2 in Annex F, part of the produced CO_2 from the outdoor storage is emitted to air immediately and part of the CO_2 is dissolved in the slurry. However, in this life cycle assessment, it is calculated as all the CO_2 is emitted to air immediately, which makes the interpretation of the sources easier, as detailed in section F.2.

H.5.6 Emissions of NH_3

In this project, the ammonia emissions are calculated using the same assumption as for the reference scenario: According to Poulsen et al. (2001), the emission of NH_3–N is 2% of the total-N in the slurry “ex-housing” (i.e. “ex-separation” in the present case). This corresponds to NH_3–N emissions of 0.1077 kg per 1000 kg of separated liquid.

H.5.7 Emissions of N_2O, NO-N and N_2-N

As in Annex F, section F.5.7, the N_2O emissions from the outdoor storage is calculated based on the IPCC guidelines (IPCC, 2006), using the total-N content of the slurry “ex-separation”. This gives a N_2O emission of 0.03244 kg N_2O-N per 1000 kg liquid fraction [3]. As mentioned in section F.5.7 it is acknowledged that the N_2O emissions may in fact be lower than this estimate due to the lower DM content in the liquid fraction (and thereby a lower potential for easily converted VS content).

The NO-N and N_2-N emissions were calculated in the same way as in Annex A, i.e. based on the study of Dämmgen and Hutchings (2008). In their study, they assumed that the emission of nitrogen monoxide (NO) is the same as the direct emission of nitrous oxide (N_2O) (measured as NO-N and N_2O-N). Furthermore, they assumed that emission of nitrogen (N_2) is three times as

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[3] The content of total-N “ex-separation” is 5.387 kg/1000 kg liquid fraction (table H.2). The content of total-N in the reference slurry is 5.48 kg per 1000 kg slurry ex-housing (table A.1, Annex A). The direct N_2O emissions in the reference scenario were 0.033 kg N_2O-N per 1000 kg slurry ex-housing (table A.11, Annex A). Therefore, the direct N_2O-N emissions are calculated as: 0.033 kg N2O-N * (5.387 kg/ 5.48 kg) = 0.03244 kg N_2O-N per 1000 kg liquid fraction.

high as the direct emissions of nitrous oxide (N_2O) (measured as N_2-N and N_2O-N).

As regarding the total NO_x emissions ($NO_x = NO + NO_2$), it was assumed, as in Annex A, that $NO_x = NO$. This is because it has not been possible to find data on NO_2.

Therefore, this means that the NO-N emissions (and thereby the NO_x-N emissions) correspond to 0.03244 kg per 1000 kg liquid fraction and the N_2-N emissions correspond to 0.09732 kg per 1000 kg liquid fraction.

The indirect N_2O-N emissions can be calculated as described by IPCC guidelines (IPCC, 2006), i.e. as 0.01 * (NH_3-N + NO_x-N). This gives indirect N_2O-N emissions of 0.0014 kg per 1000 kg liquid fraction.

H.5.8 Life cycle data and mass balances for storage of liquid fraction

Table H.3 summarizes the life cycle inventory data for the storage of liquid fraction and presents the comparison with the storage emissions in Annex A. It must be emphasized that 1000 kg liquid fraction do ***not*** correspond to 1000 kg slurry ex-animal, so the values of Annex A versus Annex H are not directly comparable. Values from Annex A were only included since they were needed for the calculation of many of the emissions.

Table H.4 presents the mass balance of the liquid fraction in order to establish its composition after the storage. In this table, it can be noticed that the change of DM is estimated as the losses of N and C. It is acknowledged that this is a rough estimation, as other elements of greater molecular weight may also be lost (e.g. dissolved O_2). The estimated DM change shall therefore be seen as a minimum change, the actual DM change may in fact be greater than the one taken into account in this study.

Table H.3
Life cycle data for storage of the liquid fraction. All data per 1000 kg of liquid fraction “ex-separation”.

	Reference pig slurry (scenario A)	Liquid fraction (fattening pig slurry) (scenario H)	Comments
Input			
Liquid fraction “ex-separation”		1000 kg	The emissions are calculated relative to this.
Slurry “ex-housing”	1000 kg		
Water	86 kg	86 kg	
Concrete slurry store	Included	Included	As in scenario A.
Cut straw	2.5 kg	2.5 kg	As straw is regarded as a waste product from cereal production (rather than a co-product), the life cycle data of straw production are not included.
Output			
Slurry “ex-storage”	1086 kg	1086 kg	
Energy consumption			
Electricity		1.45 kWh	Electricity for pumping and stirring (see text).
Emissions to air			
Carbon dioxide (CO_2)	0.18 kg (if calculated as in Annex H :2.755 kg)	1.772 kg	Calculated from CH_4 emissions: kg CO_2 = 1.248 kg CH_4 * 1.42 (see text).
Methane (CH_4)	1.94 kg	1.248 kg	Based on IPCC methodology (IPCC, 2006), but with VS of separated liquid fraction, see text.
Ammonia (NH_3-N)	0.11 kg	0.1077 kg	NH_3-N = 2% of the total-N in the liquid fraction “ex-separation”, see text.
Direct emissions of Nitrous oxide (N_2O-N)	0.033 kg	0.03244 kg	Evaluated based on reference slurry emissions, adjusted with relative total N ratios (see text).
Indirect emissions of Nitrous oxide (N_2O-N)	0.0014 kg	0.0014 kg	0.01 kg N_2O–N per kg (NH_3–N + NO_X–N) volatilised (IPCC, 2006, table 11.3), see text.
Nitrogen monoxide (NO-N) (representing total NO_X)	0.033 kg	0.03244 kg	Estimate based on Dämmgen and Hutchings (2008), consisting of assuming that NO-N = (direct) N_2O-N * 1, see text.
Nitrogen dioxide (NO_2-N)	No data	No data	No data
Nitrogen (N_2-N)	0.099 kg	0.0973 kg	Estimate based on Dämmgen and Hutchings (2008), consisting of assuming that N_2-N = (direct) N_2O-N * 3
Discharges to water			
	None	None	Assumed to be none, as leakages from slurry tanks are prohibited in Denmark

Table H.4.
Mass balances for storage of liquid fraction

	Composition of liquid fraction AFTER separation and BEFORE storage (from table H.2) [kg per 1000 kg liquid fraction]	Mass balance: Change during storage of liquid fraction [kg]	Mass balance: Amount after storage of liquid fraction [kg]	Composition of liquid fraction AFTER storage [kg per 1000 kg liquid fraction AFTER storage]
Total mass	1000 kg	86 kg	1086 kg	1000 kg
Dry matter (DM)	51.76 kg	- 1.688 kg [c)]	50.072 kg	46.11 kg
Total-N	5.387 kg	- 0.270 kg [a)]	5.117 kg	4.712 kg
Total-P	1.0833 kg	No change	1.0833 kg	0.9975 kg
Potassium (K)	2.9187 kg	No change	2.9187 kg	2.688 kg
Carbon (C)	24.728 kg	- 1.418 kg [b)]	23.31 kg	21.46 kg
Copper (Cu)	0.030189 kg	No change	0.030189 kg	0.0278 kg
Zinc (Zn)	0.088361 kg	No change	0.088361 kg	0.08136 kg

[a] Changes in total N: 0.1077 kg NH_3-N + 0.03244 kg N_2O-N + 0.03244 kg NO-N + 0.0973 kg N_2-N = 0.270 kg N

[b] Changes in total C: 1.772 kg CO2 * 12.011 [g/mol] /44.01 [g/mol] + 1.248 kg CH4 * 12.011 [g/mol] /16.04 [g/mol] = 1.418 kg C

[c] The change in DM is assumed to be identical to the sum of the loss of N and C

H.6 Transport of liquid fraction to field

The transport of the liquid fraction to field is assumed to be identical to the transport of the untreated slurry in Annex A. Accordingly the same assumptions have been applied.

This means that the process “Transport, tractor and trailer” from the ecoinvent database has been used (Nemecek and Kägi, 2007, p.204), for a distance of 10 km. This includes the construction of the tractor and the trailer. As the transport by trucks (instead of by tractor with a trailer) is required by law in Denmark when the slurry is transported for distances greater than 10 km, Wesnæs et al. (2009) carried out a sensitivity analysis with a transportation distance of 32 km (involving transport by truck). Yet, they found that the transport distance of slurry from the storage to the field had no significance on the environmental impacts they assessed. Therefore, the transport distance from storage to field is fixed to 10 km in the present project.

H.7 Field processes (liquid fraction)

H.7.1 General description

The main principles for the field processes for the liquid fraction in this annex are basically the same as for the field processes for the liquid fraction in Annex F. However, as the composition of the liquid fraction is different, the emissions will be different from Annex F, as the emissions depend on the composition of the liquid fraction (but they are still based on the same calculation methods).

H.7.2 Emissions of CH_4 and CO_2

As described in Annex F, section F.7.2, the CH_4 emissions on the field are assumed to be negligible, as the formation of CH_4 requires an anaerobic environment, which is, under normal conditions, not the case in the top soil.

CO_2 emissions and C-binding in the soil are modelled by the dynamic soil organic matter model C-TOOL (Petersen et al., 2002; Gyldenkærne et al., 2007). The development in organic soil N is modelled by assuming a 10:1 ratio in the C to N development.

H.7.3 Emissions of NH_3

The NH_3-N emissions ***during application*** were calculated as in the reference scenario, i.e. 0.5 % of the NH_4^+-N "ex-storage". This is based on Hansen et al. (2008). Yet, Hansen et al. (2008) calculated NH_4^+-N "ex-storage" as 79 % of the total N (instead of 75 % as assumed in this study). In this specific case, because the NH_3-N emissions are calculated based on Hansen et al. (2008), the NH_4^+-N will be evaluated with the figures presented by Hansen et al. (2008), as it was done in Annex A.

The NH_3-N emissions for the period after application are calculated by using the same method as described in Annex F, section F.7.3. Therefore, they are estimated as 50% of 0.138 kg NH_3-N per kg TAN-N in the pig slurry, assuming that the TAN (NH_3+NH_4^+), at the liquid fraction pH, corresponds to NH_4^+ only, and evaluating NH_4^+-N as 79 % of the total N (as these data are also based on Hansen et al., 2008). As this figure includes the NH_3-N emissions ***during application*** mentioned above, these are subtracted.

H.7.4 Emissions of N_2O-N and NO_X-N and N_2-N

Direct and indirect N_2O-N emissions as well as emissions of NO_X-N were calculated as in the reference scenario (section A.5.3 and A.5.4 in Annex A). This means that the direct emissions of N_2O-N are evaluated as 0.01 kg N_2O-N per kg N in the ex-storage liquid fraction (table 11.1 in IPCC (2006)). Yet, it is acknowledged that this may overestimate the N_2O emissions occurring from the spreading of the liquid fraction, as the C/N ratio of the liquid fraction is lower than the C/N ratio of the non-separated slurry. In fact, according to Møller et al. (2007c), the centrifugal separation mainly transfers the organic N to the solid fraction, while the dissolved NH_4^+ goes in the liquid fraction. A higher NH_4-N content involves more N in a form directly available for plants. This means that less N shall be available to microorganisms for nitrification (where NO_3^- is formed), and thus, the potential for denitrification (where NO_3^- is reduced to N_2O, and subsequently to N_2) is reduced. According to Amon et al. (2006), a lower C/N ratio also reduces the potential for N immobilisation in the soil N pool, and thereby the availability of N for denitrification.

The indirect N_2O-N emissions ***due to ammonia and NO_x*** are evaluated as 0.01 kg N_2O-N per kg of (NH_3 + NO_X) volatilized. The indirect N_2O-N emissions ***due to nitrate leaching*** correspond to 0.0075 kg N_2O-N per kg of N leaching.

The emissions of NO_X-N are calculated as 0.1* direct N_2O-N, based on Nemecek and Kägi (2007).

The N_2-N emissions are based on the estimates from SimDen (Vinther, 2004). For soil type JB3 the N_2-N:N_2O-N ratio is 3:1 and for soil type JB6 the N_2-N:N_2O-N ratio is 6.

H.7.5 Calculation of liquid fraction fertilizer value

The fertilizer value for liquid fraction is calculated and detailed in section H.23.

H.7.6 Nitrate leaching

In order to calculate N leaching values, the same simplifying assumption as in Annex C is used: the liquid fraction, once the respective ammonia losses have been subtracted, can be modeled as: a given proportion of slurry + a given amount of mineral N. The present liquid fraction has a higher content of N relative to C, as compared to the original reference slurry. This is because the mechanical separation transfers relatively more C (i.e. 29.6%) to the fibre fraction than N (i.e. 6.8%). As the amount of organic matter is one of the key properties for its effect on the N partitioning, the amount of C relative to N in the pig slurry from the reference scenario is used. The N values are taken after ammonia volatilization. The C:N proportion is 29.2 [kg C] / (4.80-0.02-0.48) [kg N] = 6.79 for the slurry and 21.7 [kg C] / (4.71-0.02-0.24) [kg N] = 4.876 for the liquid fraction. The “virtual” proportion of N assumed to affect the soil and plants as raw slurry is therefore 4.876/6.79 = 0.72, and the virtual proportion of N assumed to affect the soil and plants as mineral N is accordingly 0.28. The tables A.14 and A.15 of Annex A are therefore the basis for the calculation of N leaching, after correcting for their respective ammonia volatilizations.

H.7.7 Phosphorus leaching

For P leaching, the same assumptions as those used in Annex A were used, i.e., 10% of the P applied to field has the possibility of leaching and 6% of this actually reach the aquatic recipients, based on Hauschild and Potting (2005).

H.7.8 Cu and Zn fate

As in Annex A, it is considered that the entirety of the Cu and Zn applied will leach through the water compartment.

H.7.9 Life cycle data for field application of liquid fraction

Table H.5 presents the life cycle data for the application of ex-storage liquid fraction on the field. The results of the reference case (Annex A) are also presented for comparison purposes. However, in order to be comparable, both results must be related to the functional unit, i.e. 1000 kg slurry ex-animal.

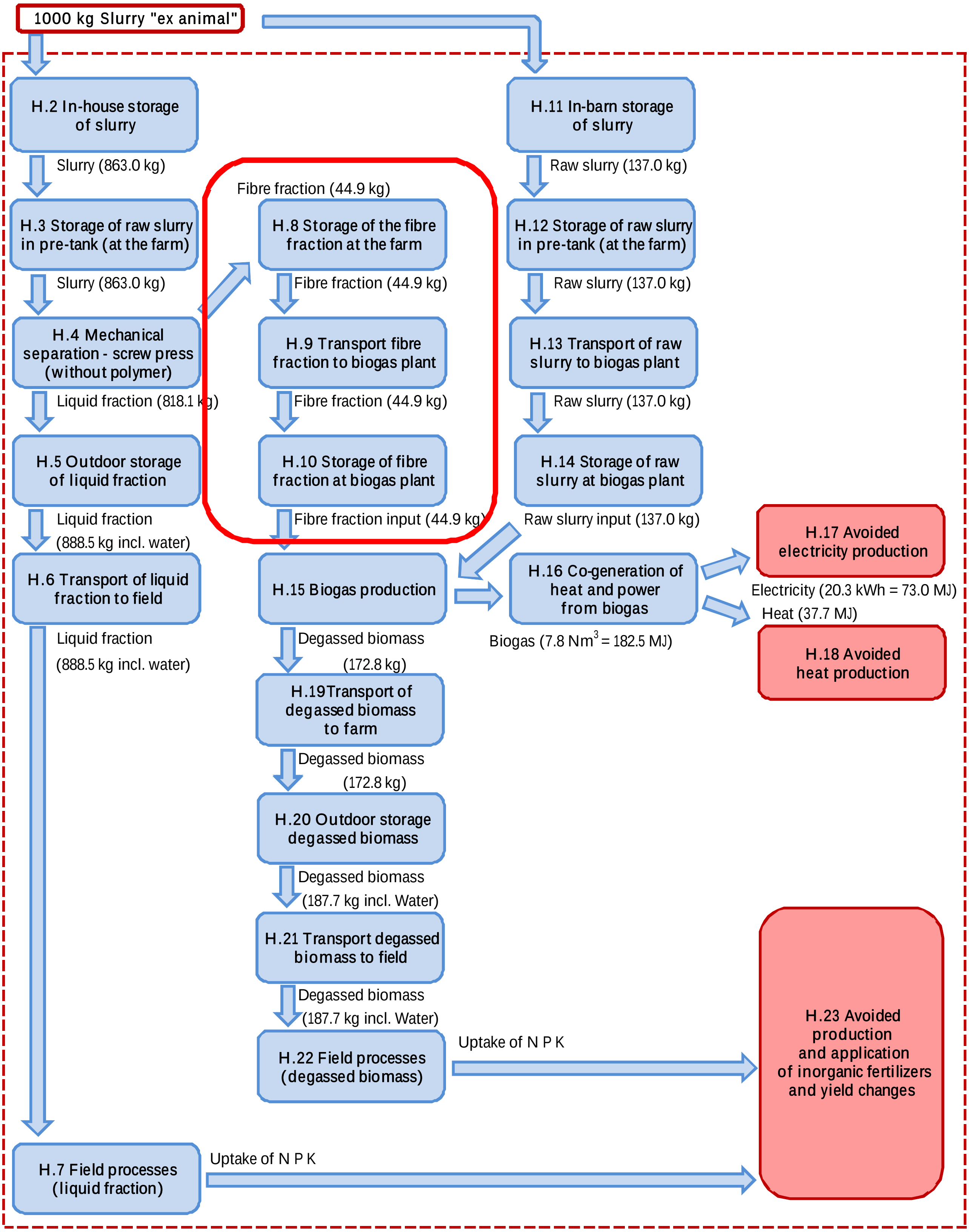
Table H.5.
Life cycle data for the field processes related with the application of liquid fraction. All data per 1000 kg of “liquid fraction ex-storage”.

	Fattening pig slurry (Annex A)	Liquid fraction after storage (Annex H)	Comments
Input			
Slurry/ liquid fraction “ex-storage”	1000 kg	1000 kg	Slurry / liquid fraction from the outdoor storage.
Output			
Slurry on field, fertiliser value	Fertiliser replacement value: 3.75 kg N 1.04 kg P 2.6 kg K	Fertiliser replacement value, N, P and K: see section H.23.	
Energy consumption			
Diesel for slurry	0.4 litres of diesel	0.4 litres of diesel	See Annex A, section A.5.1.
Emissions to air			
Carbon dioxide (CO_2) Soil JB3 Soil JB6	 81.6 kg 80.2 kg	 56.2 (73.562) kg 55.1 (73.142) kg	Modelled by C-TOOL (Gyldenkærne et al, 2007). 10 year value shown, 100 years value in parenthesis. (same as in Annex C, table C.9)
Methane (CH_4)	Negligible	Negligible	The CH_4 emission on the field are assumed to be negligible, as the formation of CH_4 requires anoxic environment (the field is aerobic) (Sherlock et al., 2002).
Ammonia (NH_3-N) during application	0.02 kg	0.0186 kg	NH3 emissions during application: 0.5% of NH4+-N “ex-storage”, the NH4+-N “ex-storage” being evaluated as 79 % of total N. Calculation based on Hansen et al. (2008), see text. 4.712 kg N * 79% * 0.5% = 0.0143 kg NH_3-N
Ammonia (NH_3-N) in period after application	0.48 kg	0.238 kg	Correspond to 50 % of the emissions calculated as in Annex A. In Annex A, it is considered that there is a loss of 0.138 kg NH_3-N per kg of NH4-N MINUS the NH3 emissions during application, see above. NH_4^+-N is here evaluated as 79% of total N. 50% * 0.138 kg NH_3-N/kg TAN-N * 79% * 4.712 kg N MINUS 0.0186 kg NH_3-N from application = 0.23825 kg NH_3-N.
Direct emissions of Nitrous oxide (N_2O-N)	0.05 kg [0.015-0.15]	0.04712 kg [0.014-0.141]	0.01 [0.003 - 0.03] kg N_2O-N per kg N “ex-storage” for application of animal wastes to soil, based on IPPC (IPCC, 2006: table 11.1).
Indirect emissions of Nitrous oxide (N_2O-N) Soil JB3 Soil JB6	0.005 kg 0.014 kg 0.011 kg	0.00261 kg 0.0146 (0.0163) kg 0.0115 (0.0128)kg	Indirect emissions due to emissions of ammonia and NO_X: 0.01 kg N_2O–N per kg (NH_3–N + NO_X–N) volatilised (IPCC, 2006). Indirect emissions due to nitrate leaching: 0.0075 kg N_2O–N per kg N leaching (IPCC, 2006). 10 year value shown, 100 years value in parenthesis.
Nitrogen oxides (NO_x-N)	0.005 kg	0.004712 kg	NO_X–N = 0.1 * direct N_2O-N according to Nemecek and Kägi (2007)
Nitrogen (N_2-N) Soil JB3 Soil JB6	 0.15 kg 0.30 kg	 0.1414 kg 0.2827 kg	Estimated from the SimDen model ratios between N_2O and N_2 by Vinther (2005), see text.

Table H.5. (Continuation)
Life cycle data for the field processes related with the application of liquid fraction. All data per 1000 kg of “liquid fraction ex-storage”.

	Fattening pig slurry (Annex A)	Liquid fraction after storage (Annex H)	Comments
Discharges to soil			
Nitrate leaching			See text. This is as in Annex C, table C.9
Soil JB3	1.91 (2.12) kg N	1.95 (2.17) kg N	
Soil JB6	1.50 (1.67) kg N	1.53 (1.70) kg N	
Phosphate leaching	0.104 kg P	0.09975 kg P	10 % of the P applied to field, see text.
Copper (Cu)	0.0276 kg	0.0278 kg	100 % of the Cu applied is assumed the leach
Zinc (Zn)	0.0824 kg	0.08136 kg	100 % of the Zn applied is assumed the leach

Processes H.8 to H.10: Handling the fibre fraction from the farm to the biogas plant before biogas is produced



H.8 Storage of the fibre fraction at the farm

As described in Annex F, section F.8, it is assumed that the storage time for the fiber fraction at the farm is very short (1-3 days) and that there are no significant emissions from this storage. See further description in Annex F.

Accordingly, the fibre fraction after the storage has the same composition as at the outlet of the separator (as presented in table H.2).

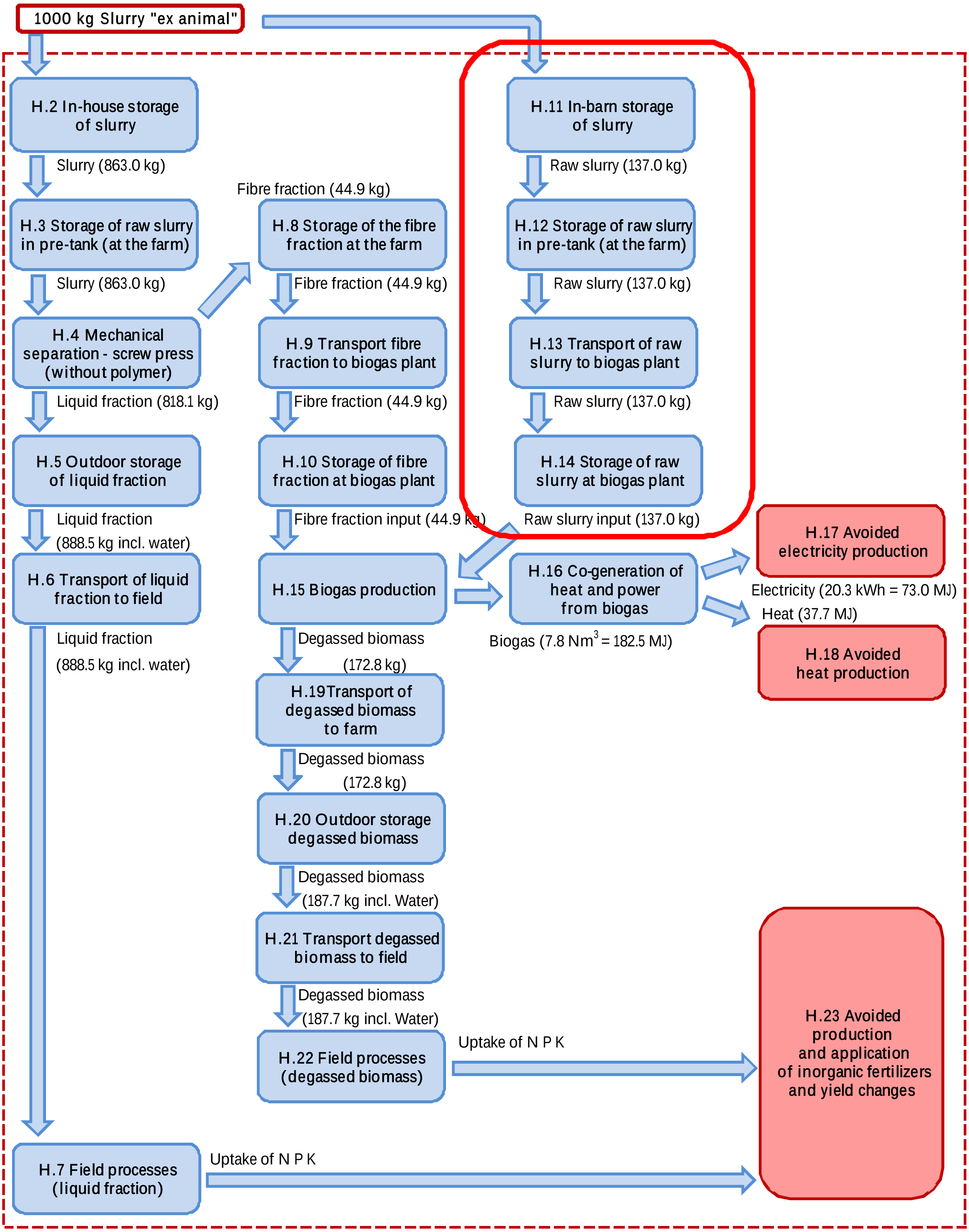
H.9 Transport of fibre fraction to biogas plant

The transport of the fibre fraction to the biogas plant in this Annex is identical to the transport of the fibre fraction in Annex F, see section F.9. It means that the calculations for the transport of the fibre fraction to the biogas plant is calculated for a transportation distance of 10.6 km (based on Laursen, 2009). The fibre fraction is transported by trucks. The transport is modelled by use of the Ecoinvent process "Transport, lorry >32t, EURO3" (Spielmann et al., 2007; table 5-124, p.96).

H.10 Storage of the fibre fraction at the biogas plant

As described in Annex F, the storage time for the fibre fraction at the biogas plant is very short – from a few days to maximum a week – and accordingly, it means that the emissions occurring during the temporal storage of the fibre fraction at the biogas plant are considered as negligible.

Processes H.11 to H.14: Handling the raw slurry input for biogas: from in-house storage to storage at the biogas plant.



1000 kg Slurry "ex animal"

H.2 In-house storage of slurry

Slurry (863.0 kg)

H.3 Storage of raw slurry in pre-tank (at the farm)

Slurry (863.0 kg)

H.4 Mechanical separation - screw press (without polymer)

Liquid fraction (818.1 kg)

H.5 Outdoor storage of liquid fraction

Liquid fraction (888.5 kg incl. water)

H.6 Transport of liquid fraction to field

Liquid fraction (888.5 kg incl. water)

H.7 Field processes (liquid fraction)

Uptake of N P K

Fibre fraction (44.9 kg)

H.8 Storage of the fibre fraction at the farm

Fibre fraction (44.9 kg)

H.9 Transport fibre fraction to biogas plant

Fibre fraction (44.9 kg)

H.10 Storage of fibre fraction at biogas plant

Fibre fraction input (44.9 kg)

H.15 Biogas production

Degassed biomass (172.8 kg)

H.19Transport of degassed biomass to farm

Degassed biomass (172.8 kg)

H.20 Outdoor storage degassed biomass

Degassed biomass (187.7 kg incl. Water)

H.21 Transport degassed biomass to field

Degassed biomass (187.7 kg incl. Water)

H.22 Field processes (degassed biomass)

Uptake of N P K

H.11 In-barn storage of slurry

Raw slurry (137.0 kg)

H.12 Storage of raw slurry in pre-tank (at the farm)

Raw slurry (137.0 kg)

H.13 Transport of raw slurry to biogas plant

Raw slurry (137.0 kg)

H.14 Storage of raw slurry at biogas plant

Raw slurry input (137.0 kg)

H.16 Co-generation of heat and power from biogas

Biogas (7.8 Nm^3 = 182.5 MJ)

H.17 Avoided electricity production

Electricity (20.3 kWh = 73.0 MJ)

Heat (37.7 MJ)

H.18 Avoided heat production

H.23 Avoided production and application of inorganic fertilizers and yield changes

H.11 In-house storage of raw slurry

The assumptions and Life Cycle Inventory data for the storage of slurry in the housing units are the same as for the reference scenario (section A.2, Annex A), and thereby the same as described in section H.2.

H.12 Storage of raw slurry in pre-tank

This process is identical to the process described in section H.2. Therefore, the same life cycle data applies here.

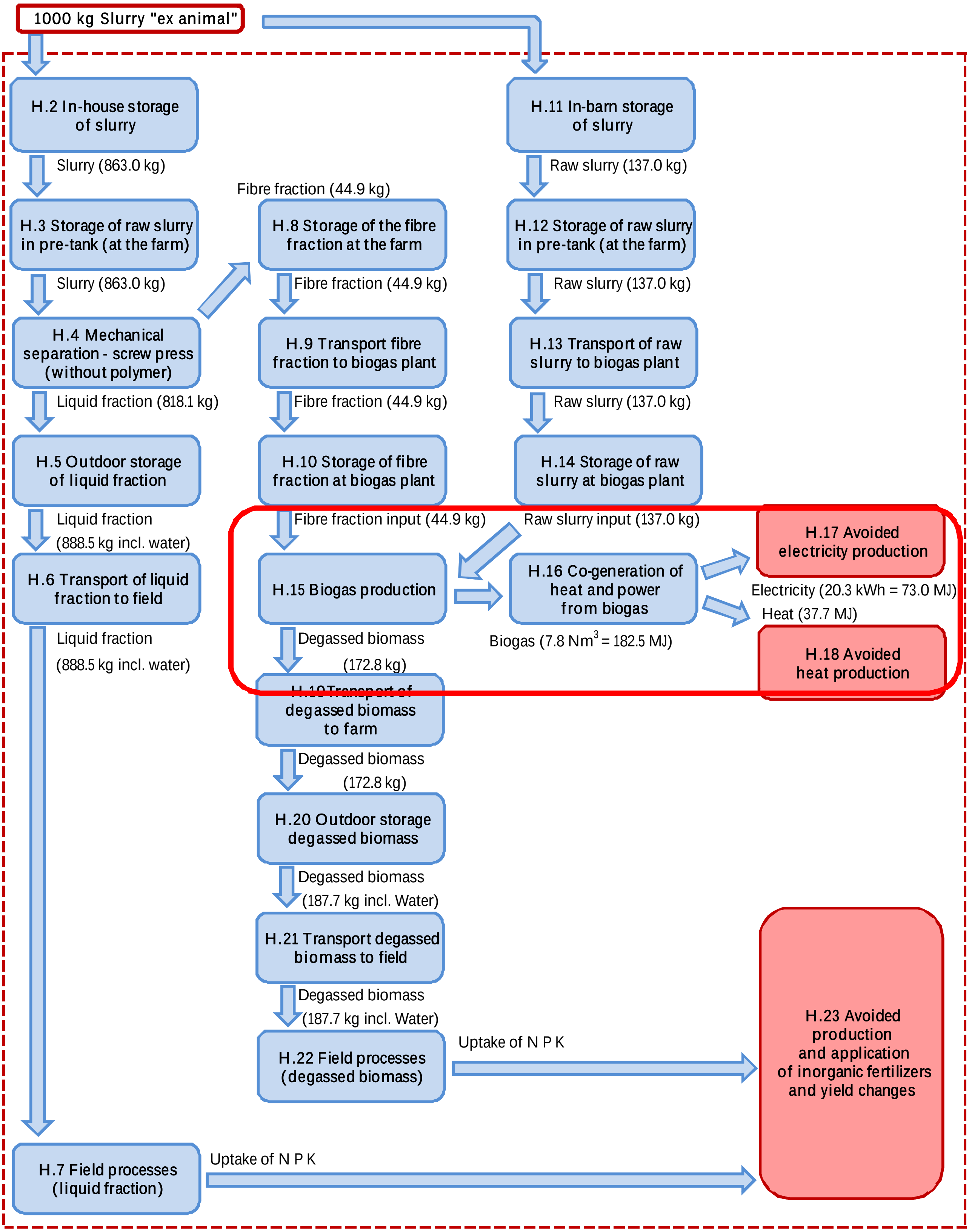
H.13 Transport of raw slurry to biogas plant

As described in Annex F, section F.13, a distance of 5 km from the farm to the biogas plant is taken into account for the transport of untreated slurry to the biogas plant.

H.14 Storage of the raw slurry at the biogas plant

As described in Annex F, section F.14, the raw slurry is stored at the biogas plant for a rather short time, since the storage capacity available at the biogas plant is limited. Therefore, no emissions were considered for this temporal stage. The composition of the raw slurry is therefore the same as the ex-housing slurry of the reference scenario, see table H.1.

Processes H.15 to H.18: Biogas production, co-generation of heat and power and avoided heat and electricity production



H.15 Biogas production

H.15.1 Biogas principles

The principles for the biogas production in this annex is identical to the principles for the biogas production described in Annex F, see section F.15.1.

However, the composition of the biomass entering the biogas plant is changed. This is described in the following.

H.15.2 Biomass mixture entering the biogas plant

The biomass mixture input in the anaerobic digester is constituted of raw slurry (which composition is identical to the ex-housing pig slurry from table H.1) and fibre fraction (which composition is shown in table H.2). According to the composition and the degradability of both fractions, the amount of both fractions in the mixture is determined in order to obtain a biomass mixture that has a DM of approximately 10% during the digestion ***in the reactor,*** in order to obtain realistic production conditions (Jensen, 2009).

According to calculations provided by Xergi (Jensen, 2009), the 1000 kg mixture of the biomass entering the biogas plant consists of:

- 753.39 kg raw slurry (ex pre-tank)
- 246.61 kg fibre fraction

The mixture composition and mass balances is shown in table H.6 below.

Table H.6.
Mass balances for the biomass entering the biogas plant, i.e. a combination of fibre fraction and raw pig slurry (slurry from **fattening pigs**).

	Composition of the raw slurry a) [kg per 1000 kg slurry]	Composition of fibre fraction b) [kg per 1000 kg fibre fraction]	Mass balances			Composition of biomass entering the biogas plant c) [kg per 1000 kg biomass]
			Amount in untreated slurry [kg]	Amount in fibre fraction [kg]	Sum of mass [kg]	
Total mass	1000 kg	1000 kg	753.39 kg	246.61 kg	1000 kg	1000 kg
Dry matter (DM)	69.7 kg	396.9 kg	753.39 /1000 * 69.7 kg = 52.511 kg	246.61 /1000 * 396.9 kg =97.8795 kg	150.39 kg	150.39 kg
Total-N	5.48 kg	7.17 kg	753.39 /1000 * 5.48 kg = 4.129 kg	246.61 /1000 * 7.17 kg = 1.768 kg	5.898 kg	5.898 kg
Total-P	1.13 kg	1.962 kg	753.39 /1000 * 1.13 kg = 0.8513 kg	246.61 /1000 * 1.962 kg = 0.4838 kg	1.335 kg	1.335 kg
Potassium (K)	2.85 kg	1.59 kg	753.39 /1000 * 2.85 kg = 2.147 kg	246.61 /1000 * 1.59 kg = 0.392 kg	2.539 kg	2.539 kg
Carbon (C)	33.3 kg	189.67 kg	753.39 /1000 * 33.3 kg = 25.088 kg	246.61 /1000 * 189.67 kg = 46.775 kg	71.862 kg	71.862 kg
Copper (Cu)	0.03 kg	0.0265 kg	753.39 /1000 * 0.03 kg = 0.0226 kg	246.61 /1000 * 0.0265 kg = 0.006547 kg	0.02915 kg	0.02915 kg
Zinc (Zn)	0.0894 kg	0.1084 kg	753.39 /1000 * 0.0894 kg = 0.06735 kg	246.61 /1000 * 0.1084 kg = 0.02672 kg	0.09407 kg	0.09407 kg

a) Same as in table H.1 (which is from ex-housing slurry in Annex A)
b) Same as in table H.2
c) Composition of biomass mixture of slurry and fibre fraction entering the biogas plant, i.e. the biomass input into the digester

In this project, the functional unit is "Management of 1000 kg slurry ex-animal". The biogas production therefore has to be related to the functional unit by the use of mass balances, i.e. the values expressed per 1000 kg of biomass mixture must be converted in order to be expressed per 1000 kg of slurry ex-animal. To do this, the amount of biomass mixture (753.39 kg raw slurry plus 246.61 kg fibre fraction) used per 1000 kg of slurry ex-animal must be calculated. This calculation can be done in 6 steps:

- ***Step 1: Defining the total amount of "ex-animal" slurry involved – contribution from the raw slurry input***
  The 753.39 kg raw slurry entering the biogas plant is "ex pre-tank ", which corresponds to the same amount of "ex-animal" slurry, since it is assumed that no water was added during the storage in the pre-tank. Therefore, the amount of raw slurry ex-animal from this input is 753.39 kg.
- ***Step 2: Defining the total amount of "ex-animal" slurry involved – contribution from the fibre fraction input***
  The 246.61 kg of fibre fraction origins from 4744.325 kg slurry ex-housing as 51.98 kg of fibre fraction is produced from 1000 kg of ex-

housing pig slurry that is mechanically separated (table H.2). The mass of slurry ex-housing is considered to be the same as the slurry ex-animal (see A.4 and A.9, Annex A). This means that 4744.325 kg of slurry ex-animal were necessary to produce the 246.61 kg of fibre fraction.

- ***Step 3: Defining the total amount of "ex-animal" slurry involved – sum of the two biomasses input***
  It means that a biomass mixture of 753.39 kg raw slurry + 246.61 kg fibre fraction origins from: 753.39 kg + 4744.325 kg = 5497.715 kg pig slurry ex-animal.
- ***Step 4: Relating the 753.39 kg of raw slurry input to the functional unit (1000 kg slurry ex-animal)***
  As the functional unit in this study is 1000 kg slurry ex-animal, the amount of "raw slurry for biogas mixture" is: 753.39 kg *1000 kg / 5497.715 kg = 137.037 kg raw slurry (ex pre-tank) per 1000 kg slurry ex-animal (and 137.037 kg raw slurry ex pre-tank corresponds to approximately 137.037 kg slurry ex-animal, as there is no water addition during the in-house storage).
- ***Step 5: Relating the 246.61 kg of fibre fraction input to the functional unit (1000 kg slurry ex-animal)***
  The amount of fibre fraction needed for the biogas mixture is: 246.61 kg *1000 kg / 5497.715 kg = 44.857 kg fibre fraction per 1000 kg slurry ex-animal (and 44.857 kg fibre fraction corresponds to 862.963 kg pig slurry ex-animal[4]).
- ***Step 6: Total biomass input needed per functional unit***
  The biomass needed for the process is then 137.037 kg pig slurry (ex pre-tank) + 44.857 kg fibre fraction = 181.894 kg "biomass mixture" entering the biogas plant per 1000 kg of slurry "ex-animal".

The mass flows in figure H.1 are based on the mass flows calculated above.

H.15.3 Energy consumption during biogas production and heat value of the biogas produced

The energy parameters for the biogas production are calculated using the same principles and calculation methods as in Annex F. However, there is one important difference: The specific methane yields for the fibre fraction is 187 Nm^3 per ton (170 Nm^3 per ton from primary digester + 10 % extra from secondary step). These data are based on Møller (2007) (the same reference as used for the corresponding data in Annex F). The fibre fraction data used are those referred to as "solids from separation by mechanical equipment (solid 2, 3)" by Møller (2007).

Accordingly, the data for the calculations are:

- The amount of VS corresponds to 80 % of DM.
- The specific methane yields for the untreated pig slurry is 319 Nm^3 per ton (290 Nm^3 per ton from primary digester + 10 % extra from secondary step)

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[4] 44.857 kg fibre fraction * (1000 kg slurry ex-animal / 51.98 kg fibre fraction) = 862.963 kg pig slurry ex-animal.

- The specific methane yields for the fibre fraction is 187 Nm^3 per ton (170 Nm^3 per ton from primary digester + 10 % extra from secondary step).
- The biogas is constituted of 65 % CH_4 and 35 % CO_2 (table F.17 in Annex F).

The calculation principles are explained in Annex F and will not be repeated here. The results of the calculations are:

- A total of 43.14 Nm^3 biogas is produced per 1000 kg of “biomass mixture” [5].
- The biogas density being 1.158 kg/Nm^3, a mass of 49.96 kg of biogas per 1000 kg of “biomass mixture” is therefore produced.
- The heat value of the biogas corresponds to 1003.4 MJ per 1000 kg biomass mixture”[6].
- During the process, both heat and electricity are consumed. See further description in section F.15.3. The electricity therefore consumed for producing the biogas corresponds to 5.57 kWh per 1000 kg “biomass mixture”[7].
- The heat consumption for the process is 116.57 MJ per 1000 kg “biomass mixture” [8].

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[5] From pig slurry: 753.39 kg slurry* 69.7 kg DM/ 1000 kg slurry * 0.8 kg VS per kg DM * 319 Nm^3 CH_4 per ton VS / 0.65 Nm^3 CH_4 per Nm^3 biogas * ton/1000 kg = 20.62 Nm^3 biogas.
From fibre fraction: 246.61 kg fibre fraction * 396.9 kg DM/1000 kg fibre fraction * 0.8 kg VS per kg DM * 187 Nm^3 CH_4 per ton VS / 0.65 Nm^3 CH_4 per Nm^3 biogas * ton/1000 kg = 22.53 Nm^3 biogas.
Total biogas produced per 1000 kg of “biomass mixture”: 43.14 Nm^3 biogas (20.62 Nm^3 from slurry + 22.53 Nm^3 from fibre fraction).

[6] This is calculated using the heat value and the total biogas produced: 6.46 kWh/Nm^3 biogas (see table F.19) * 43.14 Nm^3 biogas/1000 kg “biomass mixture” * 3.6 MJ/kWh = 1003.4 MJ/1000 kg “biomass mixture”.

[7] Estimated internal consumption of electricity in kWh per 1000 kg biomass mixture : 43.14 Nm^3 biogas/1000 kg biomass mixture x 6.46 kWh/Nm^3 biogas x 40 % engine power efficiency x 5 % internal consumption = 5.57 kWh per 1000 kg biomass mixture.

[8] It is assumed that the average temperature for the biomass is 8 °C when entering the process and that it is heated to 37°C (the process temperature). Specific heat is calculated based on the content of DM and water (calculated as 1-DM), assuming that the specific heat for DM corresponds to 3.00 kJ/kg°C and to 4.20 kJ/kg°C for water. As the DM for biomass mixture is 150.39 kg/1000 kg biomass mixture (table H.6), it involves that the water content is 1000kg – 150.39 kg = 849.61 kg/1000 kg biomass mixture. The heat consumption for heating the biomass mixture from 8°C to 37°C is thus :
For DM: 150.39 kg DM/1000 kg biomass mixture * 3.00 kJ/kg DM*°C * (37-8) °C = 13084.00 kJ/1000 kg biomass mixture;
For water : 849.61 kg water/1000 kg biomass mixture * 4.20 kJ/kg DM*°C * (37-8) °C = 103482.40 kJ/1000 kg biomass mixture;
Total : (13084.00 kJ + 103482.40 kJ) kJ/1000 kg biomass mixture * MJ/1000 kJ = 116.57 MJ/1000 kg biomass mixture.

H.15.4 Emissions of CH_4 and CO_2

As the biogas plant is constructed tight in order to reduce losses of biogas, the emissions to air during the digestion are assumed to be rather small. As described in Annex F, section F.15.4, the emission of CH_4 from the biogas plant is estimated as 1% of the produced methane.

For the emissions of CO_2, Jungbluth et al. (2007) used an emission of 1 % of the produced carbon dioxide in the biogas. In this project, the calculated ratio between emissions of CO_2 and CH_4 in anaerobic conditions will be used, i.e. 1.42 kg CO_2 per kg CH_4 (see section F.5.5 in Annex F). This, in the present case, corresponds to 0.96 % of the CO_2 produced, which is in the same magnitude as proposed by Jungbluth et al. (2007).[9]

H.15.5 Emissions of NH_3 and N_2O

As described in Annex F, section F.15.5, the emissions of NH_3 and N_2O from the biogas plant are assumed to be insignificant.

H.15.6 Life cycle data and mass balances for anaerobic digestion process

In this scenario, the biogas is not upgraded (which is necessary if it is going to be used as fuel for transport). The biogas is used for co-production of electricity and heat. Table H.7 presents the life cycle data for the anaerobic digestion process.

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[9] When calculating in accordance with the biogas composition, which is defined as 65% CH_4 and 35% CO_2 (see table F.19 in Annex F), then the ratio is 1.477 kg CO_2 per kg CH_4: 0.65 mol CH_4-C corresponds to 0.35 mol CO_2-C i.e.
1 mol CH_4-C gives 0.538 mol CO_2-C (= 0.35/0.65)
Accordingly: 16.04276 g CH_4/mol = 0.538 * 44.0098 g CO_2/mol
i.e. 1 g CH_4 = 1.477 g CO_2
1.42/1.477 = 96%

Table H.7.
Life cycle data for the anaerobic digestion process. Data per 1000 kg biomass mixture into the biogas plant.

	Biomass mixture	Comments
Input		
Biomass mixture	1000 kg	All emissions are calculated relatively to 1000 kg “biomass mixture” (i.e. 75.34% raw slurry and 24.66% fibre fraction)
Output		
Biogas	49.96 kg i.e. 43.14 Nm^3	Density 1.158 kg/Nm^3, see text.
Degassed slurry	950.04 kg	Gas output is dried. No water loss. Therefore, the only loss is the mass of the biogas : 1000 kg – 49.96 kg= 950.04 kg
Energy consumption		
Electricity	5.57 kWh	Estimated own consumption of electricity: 5 % of net production, engine efficiency of 40 %, see text. Electricity from the grid.
Heat	116.57 MJ	Heating the biomass from 8°C to 37°C, see text. Heat from the co-generation unit.
Emissions to air		
Carbon dioxide (CO_2)	0.285 kg	1.42 kg CO2 per kg CH4. 0.201 kg CH4 * 1.42 kg CO2 per kg CH4.= 0.285 kg CO2
Methane (CH_4)	0.201 kg	1% of the methane content of the biogas is assumed to be emitted to the environment. 43.14 Nm^3 biogas * 65% CH4 * 0.717 kg/Nm^3 * 1% = 0.201 kg CH4.
Ammonia (NH_3-N)		Assumed to be insignificant, see text
Nitrous oxide (N_2O-N)		Assumed to be insignificant, see text
Nitrogen oxides (NO_X)		Assumed to be insignificant, see text
Nitrogen monoxide(NO)		Assumed to be insignificant, see text
Nitrogen(N_2)		Assumed to be insignificant, see text
Hydrogen sulphide (H_2S)		Assumed to be insignificant compared to the emissions from the following co-production of electricity and heat.
Odour		No data
Emissions to water		
		No emissions to water
Emissions to soil		
		No emissions to soil

The composition of the degassed slurry after biogas production is shown in table H.8. It is based on mass balances from data presented in table H.7 for the total mass, the DM content and the total N.

Table H.8.
Mass balances for the biogas mixture before and after the biogas plant

	Composition of Mixture of slurry and fibre fraction entering the biogas plant [kg per 1000 kg biomass mixture]	Mass balance: Change during biogas production [kg]	Mass balance: Amount after biogas production [kg]	Composition of Degassed biomass after biogas production a) [kg per 1000 kg degassed biomass]
Total mass	1000 kg	- 49.96 kg b)	950.04 kg	1000 kg
Dry matter (DM)	150.39 kg	- 49.96 kg c)	950.04 kg	105.71 kg
Total-N	5.898 kg	No change	5.898 kg	6.2069 kg
Total-P	1.335 kg	No change	1.335 kg	1.4054 kg
Potassium (K)	2.539 kg	No change	2.539 kg	2.6728 kg
Carbon (C)	71.862 kg	- 23.44 kg d)	48.426 kg	50.973 kg
Copper (Cu)	0.02915 kg	No change	0.02915 kg	0.0307 kg
Zinc (Zn)	0.09407 kg	No change	0.09407 kg	0.0990 kg

a) All the data are the same as in the precedent column, but adjusted to be expressed per 1000 kg of degassed mixture, instead of per 950.04 kg of degassed mixture.
b) This loss corresponds to the biogas produced, expressed in mass terms.
c) No water loss and therefore change in dry matter is equal to change in total mass.
d) This corresponds to the losses in the biogas itself and the losses that occurred during the digestion process:
Losses in the biogas are calculated as the sum of CH_4-C and CO_2-C: (43.14 Nm^3 biogas * 65 % CH_4 * 0.717 kg CH_4/Nm^3) * (12.011 g/mol /16.04 g/mol) + (43.14 Nm^3 biogas * 35 % CO_2 * 1.977 kg CO_2/Nm^3) * (12.011 g/mol /44.01 g/mol) = 23.2 kg C
Losses from the digestion process are the aggregated losses as CO_2-C + CH_4-C: 0.285 kg CO_2 * (12.011 g/mol /44.01 g/mol) + 0.201 kg CH_4 * (12.011 g/mol /16.04 g/mol) = 0.23 kg C
Total C loss : 23.2 kg C + 0.23 kg C = 23.44 kg C.

H.15.7 Material consumption for the anaerobic digestion plant

The materials for the anaerobic digestion plant are identical to the material consumption for the anaerobic digester in Annex F, section F.15.7, see this.

H.16 Co-generation of heat and power from biogas

Also in this annex it is assumed that the biogas produced is used for the production of electricity and heat. The technology and basic methods for calculations are the same as in Annex F, however, the biogas production per 1000 kg slurry “ex-animal” is somewhat different.

As detailed in section H.15.3, the system produces 43.14 Nm^3 biogas per 1000 kg of biomass mixture. As there are 181.894 kg biomass mixture per 1000 kg slurry ex-animal (see detailed calculation in section H.15.2), this corresponds to a production of 7.847 Nm^3 biogas per 1000 kg slurry ex-animal[10].

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[10] 181.894 kg biomass mixture (per 1000 kg slurry ex-animal) * 43.14 Nm^3 / 1000 kg biomass mixture = 7.847 Nm^3 biogas per 1000 kg slurry ex-animal.

The net energy production after the co-generation unit is therefore 83.96 MJ heat plus 20.28 kWh electricity (73.01 MJ) per 1000 kg slurry ex-animal[11].

As also detailed in section H.15.3, some of the produced heat is used to fulfil the heat demand of the biogas production. The amount of heat needed for this purpose is 116.57 MJ per 1000 kg mixture input, which corresponds to 21.209 MJ per 1000 kg slurry ex-animal[12]. The heat consumption by the biogas plant thus corresponds to 21.209 MJ/ 83.96 MJ = 25.26 % of the heat produced. The surplus heat for the system is 83.96 MJ – 21.209 MJ = 62.75 MJ for the total system.

As described in Annex F (section F.16), it is considered that only 60 % of the surplus heat produced at the biogas plant is used, the remaining 40 % being wasted. Therefore, out of the 62.75 MJ per 1000 kg slurry ex-animal of net surplus heat, only 37.65 MJ (i.e. 62.75 MJ * 60%) are used to fulfil the heat demand. The wasted heat thus corresponds to 25.10 MJ.

The energy produced from the biogas can be summarized as:

- 20.28 kWh electricity (73.01 MJ) per 1000 kg slurry ex-animal, all used through the national electricity grid, low voltage electricity.
- 83.96 MJ heat per 1000 kg slurry ex-animal, of which:
    - 21.209 MJ per 1000 kg slurry ex-animal is used for fulfilling the heat demand of the biogas process itself;
    - 37.65 MJ per 1000 kg slurry ex-animal is used to fulfil national heat demand;
    - 25.10 MJ per 1000 kg slurry ex-animal is wasted.

As for Annex F, the emissions from the biogas engine were estimated from recent data from the Danish National Environmental Research Institute (DMU, 2009) (plants in agriculture, combustion of biogas from stationary engines).

Table H.9 presents the life cycle data related to the co-generation of heat and power from the biogas engine.

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[11] Heat produced: 7.8469 Nm^3 biogas (per 1000 kg slurry ex-animal) * 23.26 MJ/ Nm^3 biogas (heat value of the biogas, see table F.19 in Annex F) * 0.46 (engine efficiency for heat) = 83.96 MJ heat per 1000 kg slurry ex-animal.
Electricity produced: 7.8469 Nm^3 biogas (per 1000 kg slurry ex-animal) * 23.26 MJ/ Nm^3 biogas (heat value) * 0.40 (engine efficiency for electricity) = 73.01 MJ electricity per 1000 kg slurry ex-animal. This corresponds to 73.01 MJ * MJ/3.6 kWh = 20.28 kWh electricity per 1000 kg slurry ex-animal.

[12] There is 181.894 kg biomass mixture per 1000 kg slurry ex-animal, see section H.15.2. The heat required for the process is 116.57 MJ per 1000 kg mixture (section H.15.3). The heat needed per functional unit corresponds to: 181.894 kg biomass mixture / 1000 kg slurry ex-animal * 116.57 MJ / 1000 kg biomass mixture = 21.209 MJ per 1000 kg slurry ex-animal.

Table H.9.
Life cycle data for the co-generation of heat and power from biogas. Data per 1 MJ energy input.

	Per MJ input	Comments
Input		
Biogas	0.043 Nm^3 (1 MJ)	Amount of biogas corresponding to an energy content of 1 MJ input.[1 MJ/23.26 MJ/Nm^3] = 0.043 Nm^3.
Co-generation unit	5.0 E-9 p	Engine, generator, electric parts etc. divided by lifetime (Data from Jungbluth et al., 2007, table 13.20 of page 259)
Lubricating oil	3.0 E-5 kg	Production and disposal of used mineral oil included (Data from Jungbluth et al., 2007, table 13.20 of page 259)
Output		
Heat Of this: Used for biogas plant Surplus heat	0.46 MJ 0.116 MJ 0.344 MJ	The efficiency of the heat production is 46% (see table H.17) The heat consumption used by the biogas plant is 25.26 % : 0.46 MJ * 25.26 % = 0.116 MJ. Surplus heat: 0.46 MJ – 0.116 MJ = 0.344 MJ
Electricity	0.40 MJ	The electricity efficiency is 40% (see Annex F, table H.19)
Emissions to air		
Carbon dioxide (CO_2)	8.36 E-2 kg	DMU (2009)
Carbon monoxide (CO)	2.73 E-4 kg	DMU (2009)
Methane (CH_4)	3.23 E-4 kg	DMU (2009)
Non-methane volatile organic compounds (NMVOC)	1.40 E-5 kg	DMU (2009)
Ammonia (NH_3-N)		No data
Nitrous oxide (N_2O)	1.59 E-7 kg	DMU (2009)
Nitrogen oxides (NO_X)	5.40 E-4 kg	DMU (2009)
Nitrogen monoxide(NO)		No data
Nitrogen(N_2)		No data
Particulates PM_{10} $PM_{2.5}$	 4.51 E-7 kg 2.06 E-7 kg	DMU (2009)
Hydrogen sulphide (H_2S)		No data
Sulphur dioxide (SO_2)	1.92 E-5 kg	DMU (2009)
Odour		No data
Emissions to water		
		No emissions to water
Emissions to soil		
		No emissions to soil

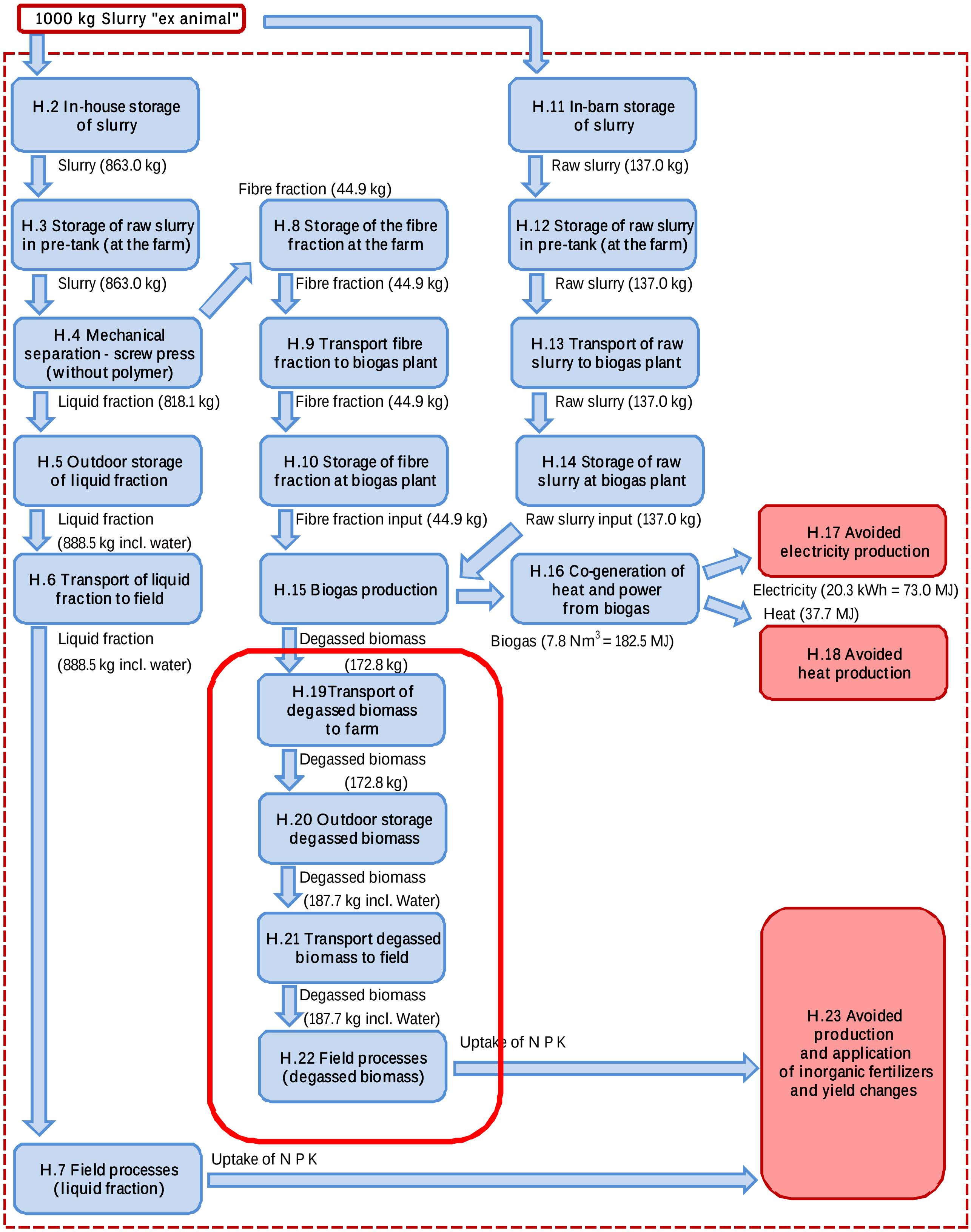
H.17 Avoided electricity production

The electricity that is replaced is the marginal electricity as described in Annex A, following the same principles as in Annex F, see section F.17. However, the amount of replaced electricity (detailed in section H.16) is different than in Annex F.

H.18 Avoided heat production

The avoided heat production is described in Annex F, section F.18. However, the amount of replaced heat (detailed in section H.16) is different than in Annex F.

Processes H.19 to H.22: Fate of the degassed biomass



H.19 Transport of the degassed biomass to the farm

The transport of the degassed biomass to the farm is identical to the process from Annex F, "Transport of the degassed liquid fraction" – except that the amount is different. Accordingly, the transport distance is 5 km.

H.20 Outdoor storage of the degassed biomass

H.20.1 General description

The outdoor storage of the degassed biomass is assumed to be mostly identical to the outdoor storage of the reference slurry in Annex A, including some adjustments in order to take the "degassed" perspective into account.

The degassed biomass is thus stored in an outdoor concrete tank covered with a floating layer consisting of 2.5 kg of straw per 1000 kg slurry stored. As in section H.5.1, the life cycle data of straw production are not included in this study, as straw is regarded as a waste product from cereal production (rather than a co-product).

H.20.2 Addition of water

The degassed biomass will be diluted by precipitation in the same amount as described in H.5.2, i.e. a total of 86 kg of water.

H.20.3 Electricity consumption

It is assumed that the electricity consumption is identical to the electricity consumption for the storage of the reference slurry in Annex A. Accordingly, the electricity for pumping and stirring is taken from table A.10 (Annex A).

The electricity consumption thus involves : the consumption for stirring when straw is added (1.2 kWh per 1000 kg slurry), the consumption for stirring (1.2 kWh per 1000 kg slurry) and pumping (0.5 kWh per 1000 kg slurry), before application to the field. This gives an electricity consumption of 2.9 kWh per 1000 kg slurry.

Note, that for the liquid fraction in section H.5.3, the energy consumption is adjusted by a reduction of 50 %, in order to account for the fact that the liquid fraction will offer less resistance during the pumping and stirring than does the raw slurry. As the degassed fibre fraction has a DM content (105.71 kg DM per kg degassed biomass, see table H.8) that is even higher than the DM content of the reference slurry "ex-housing" (69.7 kg DM per kg slurry "ex-housing", see table A.1 in Annex A), the energy consumption for pumping and stirring has not been reduced.

H.20.4 Emissions of CH_4

It has not been possible to find high quality data about the CH_4 emissions occurring during the storage of degassed biomass. Yet, in the latest Danish national inventory report for greenhouse gases, Nielsen et al. (2009) calculated the absolute CH_4 reduction of biogas-treated slurry by using the

IPCC methodology[13], coupled with a reduction potential factor of 50 % in the case of pig slurry. When applying this equation, Nielsen et al. (2009) considered the VS content of the treated slurry instead of the VS content ex-animal.

This is the methodology that will be applied in this project. The VS is estimated as 80% of the DM content. This corresponds to a VS content of 84.568 kg per 1000 kg degassed biomass (= 80% of the 105.71 kg DM per 1000 kg degassed biomass from table H.8). As regarding the reduction potential factor, in this project, the interest is not the reduction, but the emissions occurring, so a factor of (100 – 50 %) will be used instead of 50 % (which in this case does not change anything mathematically).

The CH_4 emissions are therefore calculated as: 84.568 kg VS/1000 kg degassed biomass * 0.45 m^3 CH_4/kg VS * 0.67 kg CH_4/m^3 CH_4 * 10% * (100-50) % = 1.2745 kg CH_4/1000 kg degassed biomass.

H.20.5 Emissions of CO_2

Emissions of CO_2 were estimated with the calculated ratio between emissions of CO_2 and CH_4 in anaerobic conditions, i.e. 1.42 kg CO_2 per kg CH_4 (see Annex F, section F.5.5). As mentioned in section F.5.5, part of the produced CO_2 from the outdoor storage is emitted to air immediately and part of the CO_2 is dissolved in the slurry. However, in this life cycle assessment, it is calculated as all the CO_2 is emitted to air immediately, which makes the interpretation of the sources easier, as detailed in section H.2.

This gives a CO_2 emission of 1.42 kg CO_2 per kg CH_4 * 1.2745 kg CH_4/1000 kg degassed biomass = 1.810 kg CO_2.

H.20.6 Emissions of NH_3

Hansen et al. (2008) states that there are no clear differences between the ammonia (NH_3) emissions from degassed slurry and untreated slurry. On one hand, the lower content of dry matter might reduce the emission of ammonia, on the other hand, TAN concentration and pH of degassed slurry are higher, which both increase the potential for ammonia emissions. Yet, Sommer (1997), who measured the NH_3 volatilization from both covered (one tank covered by straw and one tank covered by clay granules) and uncovered storage tank containing digested slurry, concluded that ammonia volatilization from the covered slurry was insignificant.

The ammonia emissions occurring during the storage of the degassed biomass are therefore calculated using the same assumptions as for the reference scenario, i.e. the emission of NH_3–N are 2% of the total-N, based on Poulsen et al. (2001). The total N being 6.2069 kg N/1000 kg degassed biomass, the NH_3-N emissions are 0.124 kg NH_3-N per 1000 kg degassed biomass.

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[13] According to IPCC (2006), the methane emission can be calculated as:
CH_4 [kg] = VS [kg] * B_0 * 0.67 [kg CH_4 per m^3 CH_4] * MCF
B_0 = 0.45 m^3 CH_4 per kg VS for market swine (IPCC, 2006, Table 10A-7). The MCF value used is 10 % (for liquid slurry with natural crust cover, cool climate, in table 10-17 of IPCC (2006)). This is also the MCF recommended under Danish conditions by Nielsen et al. (2009).

H.20.7 Emissions of N_2O,-N NO-N and N_2-N

In the reference scenario, the direct N_2O-N emissions for storage were based on IPCC guidelines (IPCC, 2006). However, the IPCC methodology does not provide any emission factor for storage of degassed biomass. The fact that the biomass is degassed involves a reduction in the N_2Oemissions, as part of the most easily converted dry matter was removed during the biogas production (Mikkelsen et al., 2006).

Yet, as for the CH_4 emissions, the latest Danish national inventory report for greenhouse gases (Nielsen et al., 2009) considered a reduction potential factor for estimating the reductions in N_2O-N emissions obtained when the slurry is biogas-treated. In the case of pig slurry, this reduction potential factor is 40 %.

In the present project, the direct N_2O-N emissions will be estimated as in section H.5.7 (i.e. relatively to the emissions in the reference scenario but adjusted with the different N content), and this result will be multiplied by (100-40) % in order to consider the fact that the biomass is degassed.

The direct N_2O-N emissions are therefore calculated as: 0.033 kg N_2O-N/1000 kg slurry ex-housing * (6.2069 kg N in 1000 kg of degassed biomass/ 5.48 kg N in 1000 kg slurry ex-housing) * (100-40) % = 0.02243 kg N_2O-N/1000 kg degassed biomass.

The NO-N and N_2-N emissions were calculated in the same way as in Annex A, i.e. based on the study of Dämmgen and Hutchings (2008). In their study, they assumed that the emission of nitrogen monoxide (NO) is the same as the direct emission of nitrous oxide (N_2O) (measured as NO-N and N_2O-N). Furthermore, they assumed that emission of nitrogen (N_2) is three times as high as the direct emissions of nitrous oxide (N_2O) (measured as N_2-N and N_2O-N).

As regarding the total NO_x emissions ($NO_x = NO + NO_2$), it was assumed, as in Annex A, that $NO_x = NO$. This is because it has not been possible to find data on NO_2.

Therefore, this means that the NO-N emissions (and thereby the NO_x-N emissions) correspond to 0.02243 kg N_2O-N per 1000 kg degassed biomass, and the N_2-N emissions correspond to 0.06728 kg per 1000 kg degassed biomass.

The indirect N_2O-N emissions can be calculated as described by IPCC guidelines (IPCC, 2006), i.e. as 0.01 * (NH_3-N + NO_x-N). This gives indirect N_2O-N emissions of 0.00146 kg per 1000 kg degassed biomass.

H.20.8 Life cycle data and mass balances for storage of degassed biomass

Table H.10 summarizes the life cycle inventory data for the storage of the degassed biomass and presents the comparison with the storage emissions in Annex A. It must be emphasized that 1000 kg of degassed biomass do ***not*** correspond to 1000 kg slurry ex animal, so the values of Annex A versus

Annex H are not directly comparable. Values from Annex A were only included since they were needed for the calculation of some of the emissions.

Table H.11 presents the mass balances of the degassed slurry in order to establish its composition after the storage. In table H.11, it can be noticed that the change of DM is estimated as the losses of N and C. As explained in section H.5.8, it is acknowledged that this is a rough estimation, as other elements of greater molecular weight may also be lost (e.g. dissolved O_2). The estimated DM change shall therefore be seen as a minimum change, the actual DM change may in fact be greater than the one taken into account in this study.

Table H.10
Life cycle data for storage of the degassed biomass. All data per 1000 kg of degassed biomass “ex-biogas plant”.

	Reference pig slurry (scenario A)	Degassed biomass (fattening pig slurry) (scenario H)	Comments
Input			
Degassed biomass “ex-biogas plant”		1000 kg	The emissions are calculated relative to this.
Slurry “ex-housing”	1000 kg		
Water	86 kg	86 kg	
Concrete slurry store	Included	Included	As in scenario A.
Cut straw	2.5 kg	2.5 kg	As straw is regarded as a waste product from cereal production (rather than a co-product), the life cycle data of straw production is not included.
Output			
Slurry/degassed biomass“ex-storage”	1086 kg	1086 kg	
Energy consumption			
Electricity		2.9 kWh	Electricity for pumping and stirring, see text.
Emissions to air			
Carbon dioxide (CO_2)	0.18 kg (Value if calculated as in this Annex: 2.755 kg)	1.810 kg	Calculated from CH_4 emissions: kg CO_2 = kg CH_4 * 1.42 (see text).
Methane (CH_4)	1.94 kg	1.2745 kg	IPCC methodology with the VS content in the biomass, and with a reduction factor of 50 % (see text): 84.568 kg VS/1000 kg degassed biomass * 0.45 m3 CH4/kg VS * 0.67 kg CH4/m3 CH4 * 10% * (100-50) % = 1.2745 kg CH4/1000 kg degassed biomass.
Ammonia (NH_3-N)	0.11 kg	0.124 kg	NH_3-N = 2% of the total-N in the degassed biomass “ex-digestion", see text.
Direct emissions of Nitrous oxide (N_2O-N)	0.033 kg	0.02243 kg	Estimation based on the emissions in the reference scenario, but adjusted with the relative N content. A reduction factor of 40 % was considered (see text): 0.033 kg *(6.2069 kg N in 1000 kg of degassed biomass/ 5.48 kg N in 1000 kg slurry ex-housing) * (100-40) % = 0.02243 kg N2O-N/1000 kg degassed biomass.
Indirect emissions of Nitrous oxide (N_2O-N)	0.00143 kg	0.00146 kg	0.01 kg N_2O–N per kg (NH_3–N + NO_X–N) volatilised (IPCC, 2006, table 11.3), see text.
Nitrogen monoxide (NO-N) (representing total NO_X)	0.033 kg	0.02243 kg	Estimate based on Dämmgen and Hutchings (2008), consisting of assuming that NO-N = (direct) N_2O-N * 1, see text.
Nitrogen dioxide (NO_2-N)	No data	No data	No data
Nitrogen (N_2-N)	0.099 kg	0.06729 kg	Estimate based on Dämmgen and Hutchings (2008), consisting of assuming that N_2-N = (direct) N_2O-N * 3.
Discharges to water			
	None	None	Assumed to be none, as leakages from slurry tanks are prohibited in Denmark

Table H.11.
Mass balances for storage of degassed biomass

	Composition of degassed biomass AFTER biogas plant and BEFORE storage (from table H.8) [kg per 1000 kg degassed biomass]	Mass balance: Change during storage of degassed biomass [kg]	Mass balance: Amount after storage of degassed biomass [kg]	Composition of degassed biomass AFTER storage [kg per 1000 kg degassed biomass AFTER storage]
Total mass	1000 kg	86 kg	1086 kg	1000 kg
Dry matter (DM)	105.71 kg	- 1.685 kg [c]	104.03 kg	95.789 kg
Total-N	6.2069 kg	- 0.2363 kg [a]	5.971 kg	5.498 kg
Total-P	1.4054 kg	No change	1.4054 kg	1.2941 kg
Potassium (K)	2.6728 kg	No change	2.6728 kg	2.4611 kg
Carbon (C)	50.973 kg	- 1.449 kg [b]	49.52 kg	45.602 kg
Copper (Cu)	0.0307 kg	No change	0.0307 kg	0.0283 kg
Zinc (Zn)	0.0990 kg	No change	0.0990 kg	0.0912 kg

[a] Changes in total N: 0.1241 kg NH_3-N + 0.02243 kg N_2O-N + 0.02243 kg NO-N + 0.06728 kg N_2-N = 0.236 kg N

[b] Changes in total C: 1.8103 kg CO2 * 12.011 [g/mol] /44.01 [g/mol] + 1.2749 kg CH4 * 12.011 [g/mol] /16.04 [g/mol] = 1.4487 kg C

[c] The change in DM is assumed to be identical to the sum of the loss of N and C

H.21 Transport of degassed biomass to field

The transport of the degassed biomass to the field is identical to the process described in section F.6 (transport of the liquid fraction to the field).

H.22 Field processes for degassed biomass

H.22.1 General description

The field processes for the degassed biomass is assumed to be mostly identical to the field processes for the reference slurry in Annex A, including some adjustments in order to take the “degassed” perspective into account.

As in the process described in section H.7 (field processes for liquid fraction), the data from the Ecoinvent process “Slurry spreading, by vacuum tanker” (Nemecek and Kägi, 2007, p. 198) were used for the emissions related to spreading equipment “consumption”. This includes the construction of the tractor and the slurry tanker, as well as the diesel consumption. The diesel consumption due to the use of the “tanker” in the Ecoinvent process was adjusted to 0.4 litres of diesel per 1000 kg of slurry, based on Kjelddal (2009) (the same as in Annex A).

H.22.2 Emission of CH_4 and CO_2

The CH_4 emissions on the field are assumed to be negligible, as the formation of CH_4 requires an anaerobic environment, which is, under normal conditions, not the case in the top soil.

CO_2 emissions are modelled by the dynamic soil organic matter model C-TOOL (Petersen et al., 2002; Gyldenkærne et al., 2007). The development in organic soil N is modelled by assuming a 10:1 ratio in the C to N development.

H.22.3 Emissions of NH_3

Since the degassed biomass is subjected to both increasing and reducing factors as regarding the ammonia emission potential, the ammonia emissions were calculated as in the reference scenario. This is further detailed in section F.7.3 in Annex F (but without the 50% reduction factor as this reduction factor only applies for liquid fractions – and the degassed biomass is not separated).

Accordingly, the NH_3-N emissions for the period after application are calculated by using the same method as described in section H.7.3 above (but without the 50% reduction factor).

H.22.4 Emissions of N_2O and NO_X-N

The direct N_2O emissions are generally assumed to be smaller for degassed slurry than for untreated slurry (Sommer et al. 2001). This is because digested manure contains less easily decomposed organic matter than undigested manure (Börjesson and Berglund, 2007) and because more N is in a form already available to the plants (NH_4^+). This means that less N shall be available to microorganisms for nitrification (where NO_3^- is formed), and thus, the potential for denitrification (where NO_3^- is reduced to N_2O, and subsequently to N_2) is also reduced. This is also in accordance with Marcato et al. (2009), who concluded from their results that there are fewer risks for oxygen competition between the crops and soil bacteria (and therefore of N_2O emissions) with digested slurry as compared to undigested slurry. According to Sommer et al. (2001, table 2) N_2O emissions with degassed slurry are in the magnitude of 0.4 % of the applied N. Based on Sommer et al. (2001), Nielsen (2002) used, for field emissions with digested slurry, a reduction corresponding to 41 % of the emissions with raw slurry (i.e. from 34 to 20 g N_2O/ton manure) and Börjesson and Berglund (2007) assumed a reduction of 37.5 % (i.e. from 40 to 25 g N_2O per tonne of manure).

In this project, the estimate of Sommer et al. (2001) for digested slurry will be used as the best available data. This should be regarded as a rather rough estimate. A more precise value for the magnitude of this value would require either an adequate number of scientific based field measurements or detailed modelling in an appropriate tool, which has been beyond the frame of this project.

As in section H.7, indirect N_2O emissions ***due to ammonia and NO_x*** are evaluated as 0.01 kg N_2O-N per kg of (NH_3 + NO_X) volatilized. The indirect N_2O-N emissions ***due to nitrate leaching*** correspond to 0.0075 kg N_2O-N per kg of N leaching. The emissions of NO_X-N are calculated as 0.1* direct N_2O-N, based on Nemecek and Kägi (2007).

H.22.5 Emissions of N_2-N

The N_2-N emissions are based on the estimates from SimDen (Vinther, 2004). For soil type JB3 the N_2-N:N_2O-N ratio is 3:1 and for soil type JB6 the N_2-N:N_2O-N ratio is 6.

H.22.6 Calculation of degassed biomass fertilizer value

The fertilizer value for degassed biomass is calculated and detained in section H.23.

H.22.7 Nitrate leaching

The C/N ratio of the degassed biomass is higher than for pig slurry. Hence, a simplifying approach is used here, where the N “remaining” after gaseous losses and incorporation in the soil N pool is assumed to be divided between harvest and leaching in the same proportion as for pig slurry. See Annex F, section F.23.7 for further description. After the gaseous losses (table H.12), there is 3.6107 (JB3) and 3.3841 (JB6) kg N left for harvest and leaching. For the 100 years values, there is, after the gaseous losses, 5.197 (JB3) and 5.1774 (JB6) kg N left for harvest and leaching.

H.22.8 Phosphorus leaching

For P leaching, the same assumptions as those used in Annex A were used, i.e., 10% of the P applied to field has the possibility of leaching and 6% of this actually reach the aquatic recipients, based on Hauschild and Potting (2005).

H.22.9 Cu and Zn fate

As in Annex A, it is considered that the entirety of the Cu and Zn applied will leach through the water compartment.

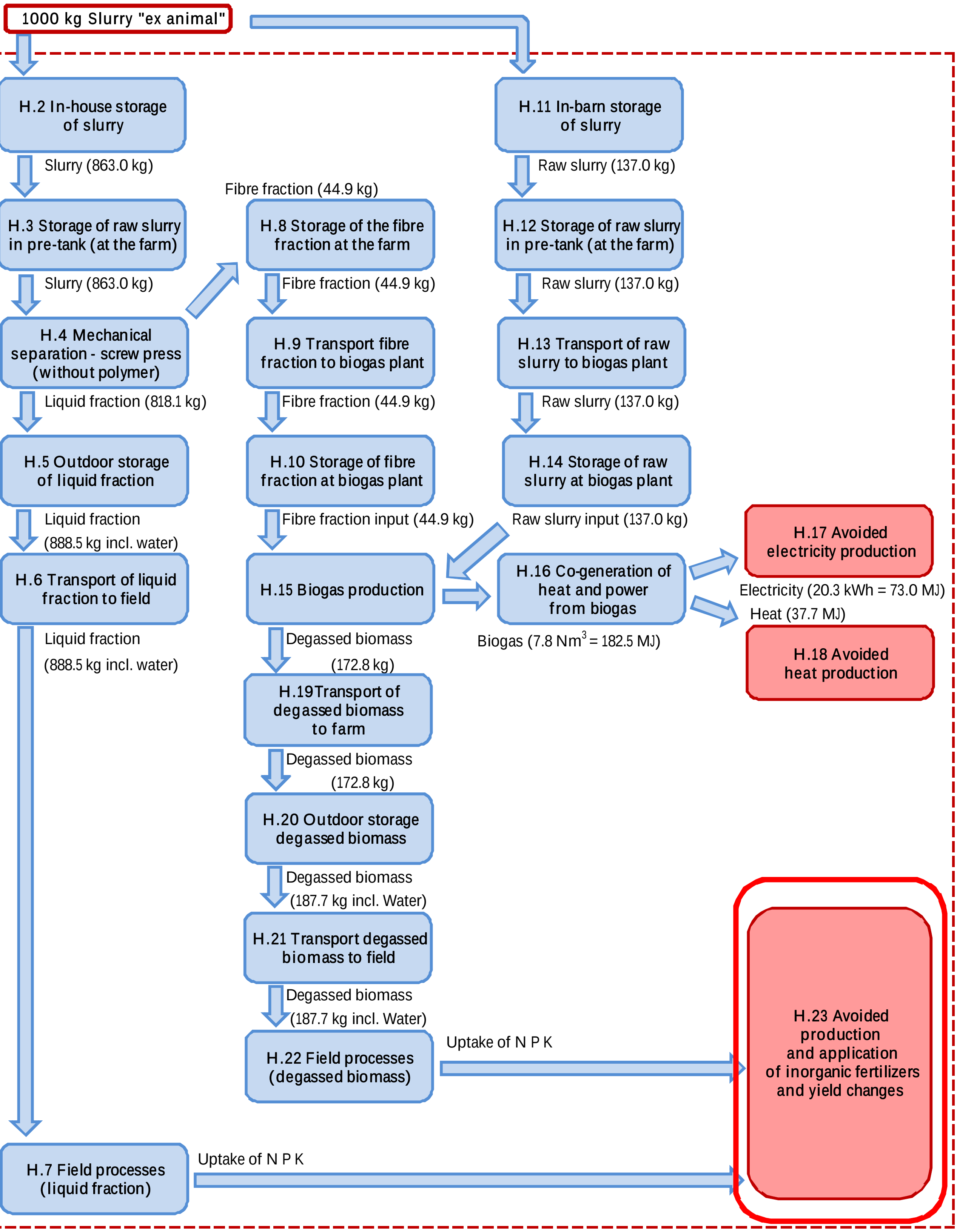
H.22.10 Life cycle data for field application of degassed biomass “ex-storage”

Table H.12 presents the life cycle data for the application of degassed biomass “ex-storage” on the field. The results of the reference case (Annex A) are also presented for comparison purposes. However, in order to be comparable, both results must be related to the functional unit, i.e. 1000 kg slurry ex-animal.

Table H.12.
Life cycle data for application of degassed biomass and field processes. All data per 1000 kg of “degassed biomass ex-outdoor storage”.

	Fattening pig slurry	Degassed biomass ex-storage	Comments
Input			
Slurry/ degassed biomass “ex-storage”	1000 kg	1000 kg	Slurry / degassed biomass from the outdoor storage. This is the reference amount of slurry, i.e. the emissions are calculated relative to this.
Output			
Slurry on field, fertiliser value	See section A.6.1.	See section H.23.	
Energy consumption			
Diesel for slurry	0.4 litres of diesel	0.4 litres of diesel	See Annex A.
Emissions to air			
Carbon dioxide (CO_2) Soil JB3 Soil JB6	 81.6 kg (99.8 kg) 80.2 kg (99.4kg)	 127.5 (156.2) kg 123.3 (155.6) kg	Modelled by C-TOOL (Gyldenkærne et al, 2007). 10 year value shown, 100 years value in parenthesis.
Methane (CH_4)	Negligible	Negligible	Negligible, see Annex A.
Ammonia (NH_3-N) during application	0.02 kg	0.0217 kg	NH3 emissions during application: 0.5% of NH4+-N “ex-storage”, the NH4+-N “ex-storage” being evaluated as 79 % of total N. 5.498 kg N * 79% * 0.5% = 0.0217 kg NH_3-N
Ammonia (NH_3-N) in period after application	0.48 kg	0.5777 kg	Correspond to 0.138 kg NH_3-N per kg NH_4^+-N in the degassed biomass (minus the NH3 emissions from application above). 5.498 kg N * 0.138 kg NH_3-N/kg TAN-N * 79% MINUS the 0.0217 kg NH_3-N from above = 0.5777 kg NH_3-N
Direct emissions of Nitrous oxide (N_2O-N)	0.05 kg [0.015-0.15]	0.055 kg	0.01 [0.003 - 0.03] kg N_2O-N per kg N “ex-storage” for application of animal wastes to soil, based on IPPC (IPCC, 2006; table 11.1).
Indirect emissions of Nitrous oxide (N_2O-N) Soil JB3 Soil JB6	0.005 kg 0.014 kg 0.011 kg	0.00605 kg 0.01478 (0.0188) kg 0.0114 (0.01508) kg	Indirect emissions due to emissions of ammonia and NO_X: 0.01 kg N_2O–N per kg (NH_3–N + NO_X–N) volatilised (IPCC, 2006) Indirect emissions due to nitrate leaching: 0.0075 kg N_2O–N per kg N leaching (IPCC, 2006).
Nitrogen oxides (NO_x-N)	0.005 kg	0.0055 kg	NO_X–N = 0.1 * N_2O-N according to Nemecek and Kägi (2007)
Nitrogen (N_2-N) Soil JB3 Soil JB6	 0.15 kg 0.30 kg	 0.165 kg 0.33 kg	Estimated from the SimDen model ratios between N_2O and N_2 by Vinther (2005), see text.
Discharges to soil			
Nitrate leaching Soil JB3 Soil JB6	 1.91 (2.12) kg N 1.50 (1.67) kg N	 1.97 (2.51) kg N 1.52 (2.01) kg N	See text
Phosphate leaching	0.104 kg P	0.129 kg P	10% of the P applied has the possibility to leach.
Copper (Cu)	0.0276 kg	0.0283 kg	See table H.11
Zinc (Zn)	0.0824 kg	0.0912 kg	See table H.11

Process H.23: Avoided production and application of mineral fertilizers and yield changes



H.23 Avoided production and application of mineral fertilizers

H.23.1 Calculation of the replaced amount of mineral fertiliser

This is calculated using the same method as in Annex F.

Table H.13.
Replaced amount of mineral N fertiliser in Annex H. All calculations per 1000 kg slurry ex-animal

Calculations
Step 1: Substitution value for fibre fraction to biogas plant Amount of fibre fraction: 44.857 kg (see figure H.1). N in fibre fraction: 7.17 kg N per 1000 kg fibre fraction (see table C.3 in Annex C). Substitution value: 50% of 7.17 kg per 1000 kg fibre fraction * 44.857 kg fibre fraction / 1000 kg = 0.16081 kg N. This is the substitution value that "belongs" to the fibre fraction that is sent to the biogas plant. This is "input" to the biogas plant.
Step 2: Acknowledging the above, make the weighted sum of the substitution values (liquid and fibre). For raw pig slurry, the substitution value is 75 %. Here rule (a) applies: "The sum of the "mineral fertiliser replacement value" of the outgoing fractions shall be the same as the "mineral fertiliser replacement value" of the ingoing slurry before separation". The mineral fertiliser replacement value of untreated, raw pig slurry is calculated based on the Danish Norm Data (DJF, 2008), which was also done in Annex A (section A.6.1). From the Danish Norm Data tables, the farmer knows the value of 5.00 kg N per kg slurry ex storage (see also table A.5 and A.1). The Danish Norm Data is what the farmer use for the accounts: 5.00 kg N per 1000 kg slurry ex storage (table A. 1). For the system, the mineral fertiliser substitution value is then: 5.00 kg N per 1000 kg slurry ex storage * 1086 kg slurry ex storage / 1000 kg slurry ex animal * 75% = 4.0725 kg N per 1000 kg slurry ex-animal. However, there is only 862.963 kg slurry being separated (see figure H.1), i.e. 4.0725 kg/1000 kg * 862.963 kg = 3.51442 kg N. • Of this 3.51442 kg N, 0.16081 kg N belongs to the fibre fraction (as calculated in step 1). • The difference i.e.: 3.51442 kg N – 0.16081 kg N = 3.35361 kg N belongs to the liquid fraction. Mineral fertiliser replacement value for the liquid fraction (at the farm): **3.35361 kg N**
Step 3: Make a weighed sum of the substitution values for the materials entering the biogas plant. Rule (b): "Mass balance in and out of Biogas Plant – i.e. the "mineral fertiliser replacement value" of the outgoing biomass is calculated in accordance with the ingoing biomass". • The raw slurry going directly to biogas plant (without separation) has a mineral fertiliser replacement value of 4.0725 kg N per 1000 kg slurry (as described under step 2 above – 75% of 5.00 kg N ex storage). The amount of this raw slurry is 137.037 kg (see figure H.1). Its mineral fertiliser replacement value is: 4.0725 kg N per 1000 kg slurry * 137.037 kg slurry/1000 kg = 0.55808 kg N per 1000 kg slurry ex-animal. This is the substitution value for the raw slurry into the biogas plant. • At the plant, a biomass mixture is made from this raw slurry and the fibre fraction from step 1, so the substitution value for this input mixture is: 0.16081 kg N (fibre fraction, step 1) + 0.55808 kg N (raw slurry, see above) = 0.71889 kg N. Mineral fertiliser replacement value for the degassed biomass: **0.71889 kg N**
Total amount of substituted mineral N fertiliser in the system 3.35361 kg N + 0.71889 kg N = **4.0725 kg N**

H.23.2 Yield changes

Using the same methods as in section F.28.3[14], the overall N difference between Scenario A and Scenario H is (in kg mineral N equivalent):

0.3182 kg N per 1000 kg slurry ex-animal for soil JB3;
0.3170 kg N per 1000 kg slurry ex-animal for soil JB6.

Accordingly, the extra corresponding wheat is:

For soil JB3: 0.3182 kg N surplus * 9.0 kg extra wheat/kg N surplus = 2.86 kg extra wheat (per 1000 kg slurry ex-animal).

For soil JB6: 0.4432 kg N surplus * 8.1 kg extra wheat/kg N surplus = 2.57 kg extra wheat (per 1000 kg slurry ex-animal).

H.23.3 Avoided P and K mineral fertilisers

As the amount of P and K in the slurry is the same as in Annex A, as there are no loss of P and K in the system, and as it is assumed that all the slurry fractions (the liquid fraction at the farm and the degassed biomass) ends in the same area, the amount of replaced mineral fertilisers are the same as in Annex A, see section A.6.

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[14] The values needed to apply the methodology presented in Annex F can be found in the sections for N leaching, namely H.7.6 and H.22.7.

Annex I. Fibre pellets from mechanical separation for biogas production – Life Cycle Inventory data

I.1 System description

This annex contains Life Cycle Inventory data for biogas production from a mixture of fibre pellets (from a Samson Bimatech energy plant that also contains a separator, see further description in Annex C, D and E) and raw untreated pig slurry. The biogas is used for co-production of heat and power.

This scenario is set up in order to answer the question: "What are the environmental benefits and disadvantages of using the fibre pellets (from Samson Bimatechs energy plant) for biogas production compared to the reference scenario for pig slurry?".

Accordingly, it is different than the scenario in Annex F, where the aim was to analyse an optimised system using "Best Available Technology" for biogas production as far as possible.

The main differences compared to Annex F are:

- At the biogas plant, the "biomass mixture" is a mixture of fibre pellets and raw pig slurry (not fibre fraction, as in Annex F and H)
- The separation technology in this annex is based on the Samson Bimatech separation technology.
- Polymer is not added to the separation (polymer is added for the separation in Annex F). It is possible to add this for the Samson Bimatech technology, but data has not been available for this. Adding polymer would give very different results for the separation than the data used in this report.
- The methane conversions rate for the fibre pellets from the Samson Bimatech separation is set to 187 Nm^3 CH_4/ton VS compared to the 319 Nm^3 CH_4/ton VS for the fibre fraction from the mechanical-chemical separation used in Annex F, based on information from Møller (2007).
- Separation after the biogas plant is not included, as this scenario is not set up to be a modelling of "best available technology" and as separation after the biogas plant is not commonly used today. Furthermore, the aim of separating the degassed biomass after the biogas plant is to recover phosphorous, and with that in mind, it would not be sensible to use a mechanical separation ***before*** the biogas plant that only separates 9.1% of the phosphorus to the fibre fraction (see table H.2 in Annex H). In this scenario, less than 16% of the phosphorous in the original pig slurry "ex-animal" actually reach the biogas plant [1] and accordingly, it is not the optimal system for phosphorous recovering.

A flow diagram for the scenario for biogas production based on the fibre pellets from the Samson Bimatech Energy Plant (including mechanically separation) and untreated slurry is shown in figure I.1. The process numbers in figure I.1 follows the numbers of the sections in this annex.

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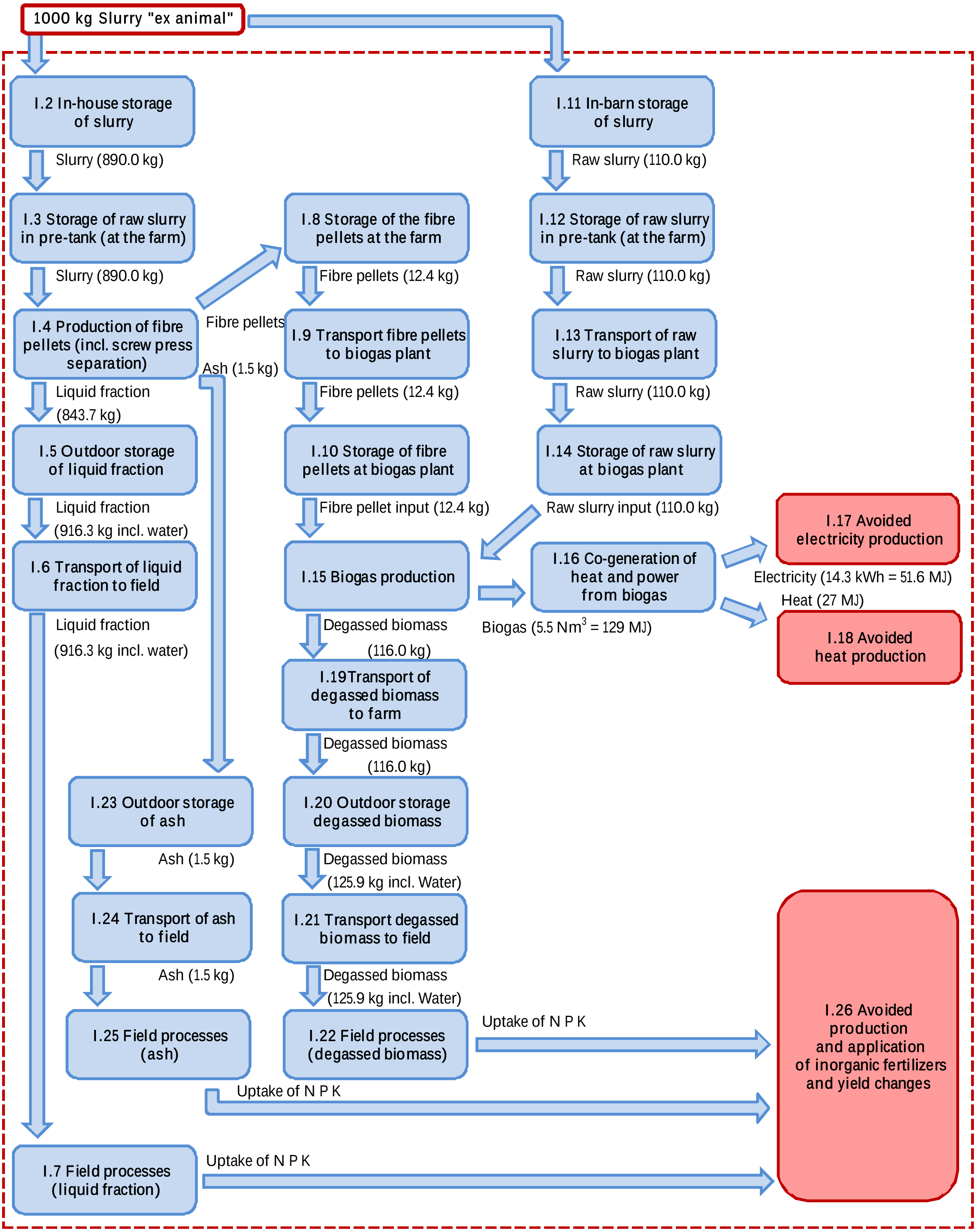
[1] The initial phosphorus content is 1.13 kg P per 1000 kg pig slurry "ex-animal". From figure I.1it can be seen that the biogas plant receive 12.4 kg fibre pellets plus 110 kg raw pig slurry. The fibre pellets contain 0.055 P (i.e. 12.4 kg * 4.433 kg P /1000 kg, see table D.1 in Annex D) and the raw slurry contains 0.1243 kg P (i.e. 110 kg raw slurry * 1.13 kg P/1000 kg), which means that a total of 0.1793 kg P reach the biogas plant. This corresponds to 15.9% (i.e. 0.1793 kg / 1.13 = 15.9%)

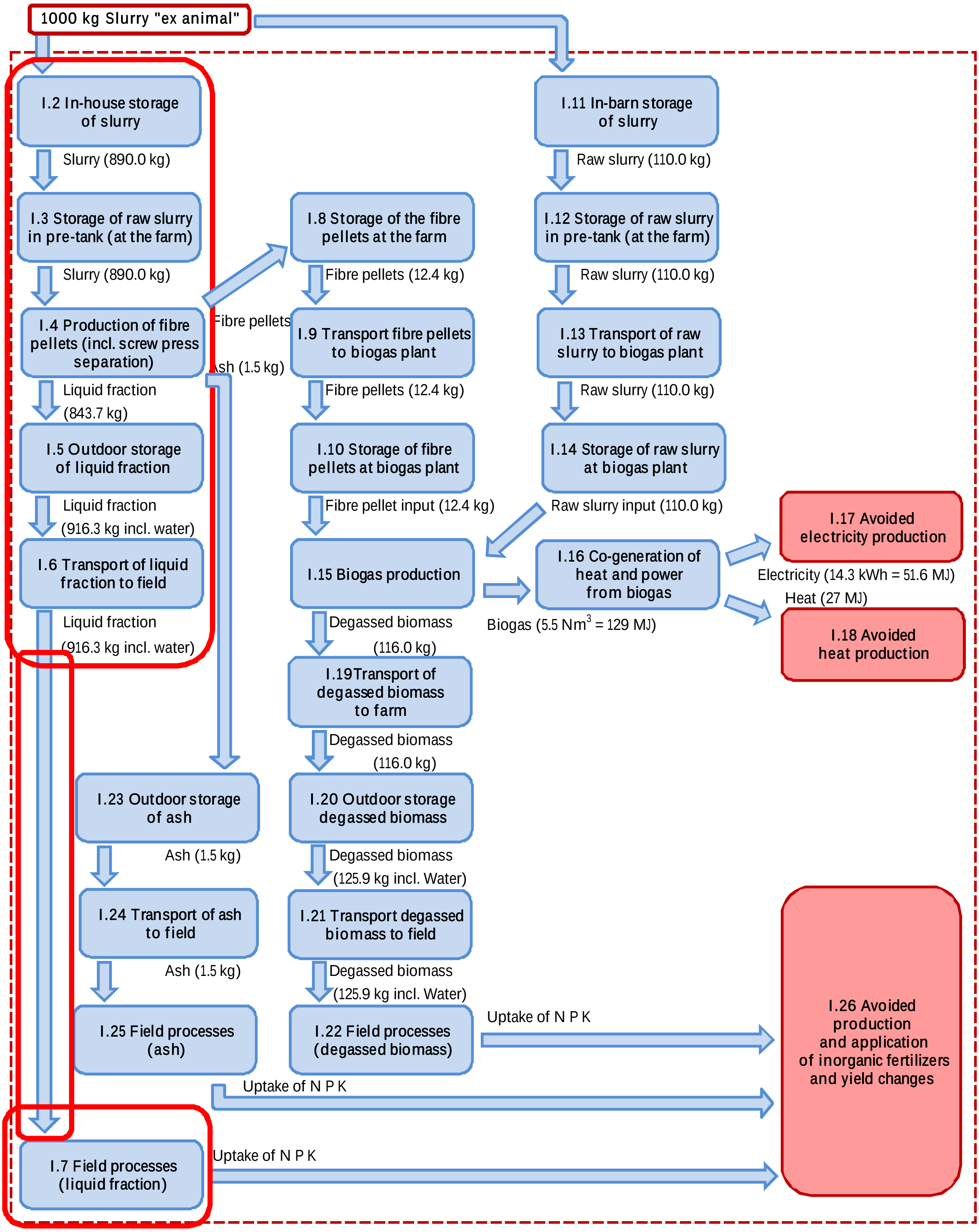
The present annex describes a total of 26 main processes, which were divided into 7 main sections:

- Section 1: Processes I.2 to I.7
  This section focus on the slurry from which the fibre pellets input in the biomass mixture (for biogas) origins. It starts with the raw slurry being produced in the pig barn and stored in the barn (I.2). The slurry is then stored in the pre-tank (I.3) and separated (I.4). This section then continues with the fate of the liquid fraction only. The liquid fraction is stored outdoor (I.5), until it is transported to the field (I.6) and used as a fertilizer (I.7).
- Section 2: Processes I.8 to I.10
  This section is a continuation of the previous, and starts with the fibre pellet output from the Samson Bimatech Energy Plant (I.4). The fibre pellets are stored on-farm (I.8), transported to the biogas plant (I.9) and temporarily stored at the biogas plant (I.10).
- Section 3: Processes I.11 to I.14
  This section focus on the raw slurry input in the biomass mixture (for biogas). It begins with the raw slurry being produced in the pig barn and stored in the barn (I.11). The slurry is then stored in pre-tank at the farm (I.12), and transported to the biogas plant (I.13). Once at the biogas plant, the raw slurry is stored temporarily (I.14).
- Section 4: Processes I.15 to I.18
  This section focuses on the biogas production (I.15) and the resulting heat and power co-generation (I.16). This co-generation avoids marginal electricity to be produced (I.17) and well as marginal heat (I.18).
- Section 5: Processes I.19 to I.22
  This section focuses on the fate of the degassed biomass. After the biogas plant, it is transported back to the farm (I.19), stored (I.20) until it is transported to the field (I.21) to be used as a fertilizer (I.22).
- Section 6: Processes I.23 to I.25
  This section focuses on the fate of the ash from the Samson Bimatech Energy Plant. After leaving the energy plant, the ash is stored (I.23) until it is transported to the field together with the liquid fraction (I.24) to be used as a fertilizer (I.25).
- Section 7: Process I.26
  Throughout this annex, the slurry is applied to field as the liquid fraction from the separation (I.7), as ash from the energy plant (I.22) and as the degassed biomass from the biogas plant (I.25). The use of the slurry and degassed biomass as organic fertilizers results in a reduced use and production of inorganic fertilizers (I.23), which is the main focus of this section.

Figure I.1.
Flow diagram for the scenario for biogas production based on fibre pellets from the Samson Bimatech Energy Plant (including the Samson Bimatech mechanical separator).



Processes I.2 to I.7: Raw slurry from which the fibre pellets origins: production, separation and fate of the liquid fraction



I.2 In-house storage of slurry

This process is identical to process H.2 from Annex H, see this.

I.3 Storage of raw slurry in pre-tank at farm

This process is identical to process H.3 from Annex H, see this.

I.4 mechanical separation and fibre pellet production

This process is identical to process E.4 from Annex E, see this.

During this process, the slurry is separated, and the fibre fraction is used for fibre pellet production. The process is taking place in the Samson Bimatech Energy Plant, which is described in Annex E, section E.4.

I.5 Outdoor storage of the liquid fraction

This process is identical to process H.5 from Annex H, see this.

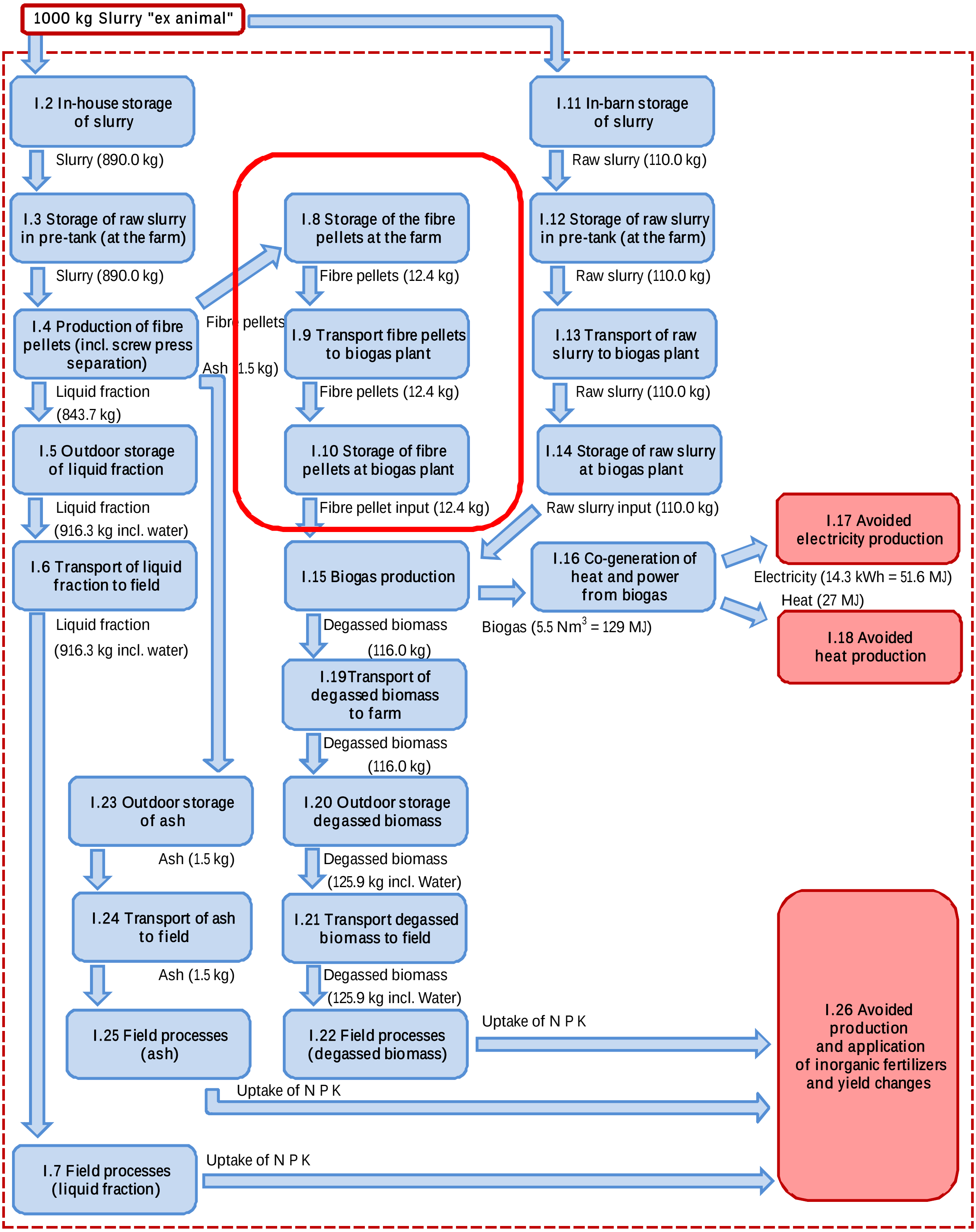
I.6 Transport of liquid fraction to field

This process is identical to process H.6 from Annex H, see this.

I.7 Field processes (liquid fraction)

This process is identical to process H.7 from Annex H, see this.

Processes I.8 to I.10: Handling the fibre pellets from the farm to the biogas plant before biogas is produced



I. 8 Storage of the fibre pellets at the farm

As described in Annex D, section D.9, it is assumed that there are no significant emissions from the fibre pellets during storage.

Accordingly, the fibre pellets after the storage has the same composition as at the outlet of the Samson Bimatech Energy Plant (as presented in table D.1 in Annex D).

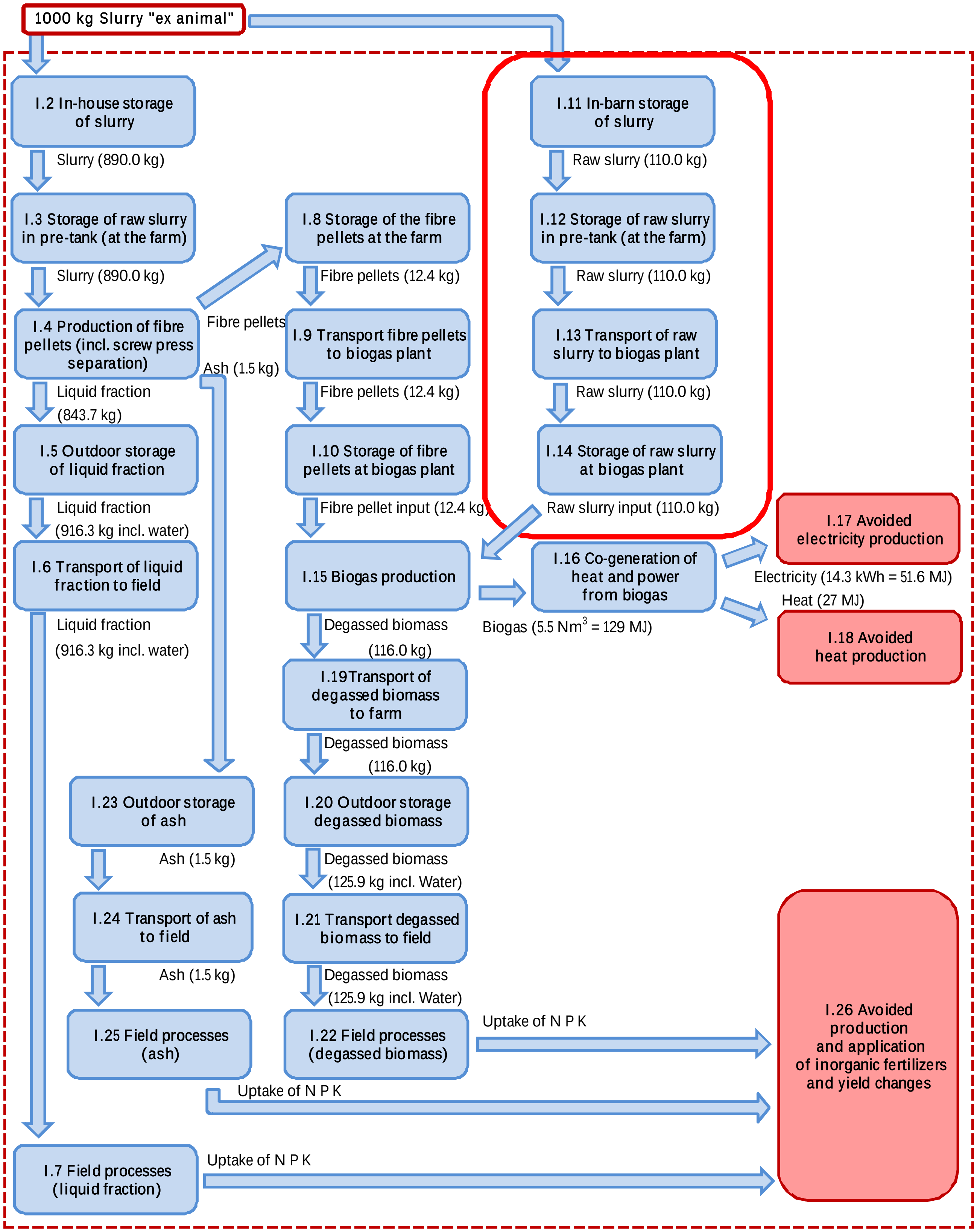
I.9 Transport of fibre pellets to biogas plant

The transport of the fibre pellets to the biogas plant in this Annex is identical to the transport of the fibre fraction in Annex F, see section F.9 (i.e. the same distance, but different amount).

I.10 Storage of the fibre pellets at the biogas plant

The storage of the fibre pellets at the biogas plant is based on the same assumptions as the storage of the fibre fraction at the biogas plant in Annex F, i.e. that the storage time for the fibre fraction at the biogas plant is very short – from a few days to maximum a week – and accordingly, it means that the emissions occurring during the temporal storage of the fibre fraction at the biogas plant are considered as negligible.

Processes I.11 to I.14: Handling the raw slurry input for biogas: from in-house storage to storage at the biogas plant.



I.11 In-house storage of raw slurry

This process is identical to process H.11 from Annex H, see this.

I.12 Storage of raw slurry in pre-tank

This process is identical to process H.12 from Annex H, see this.

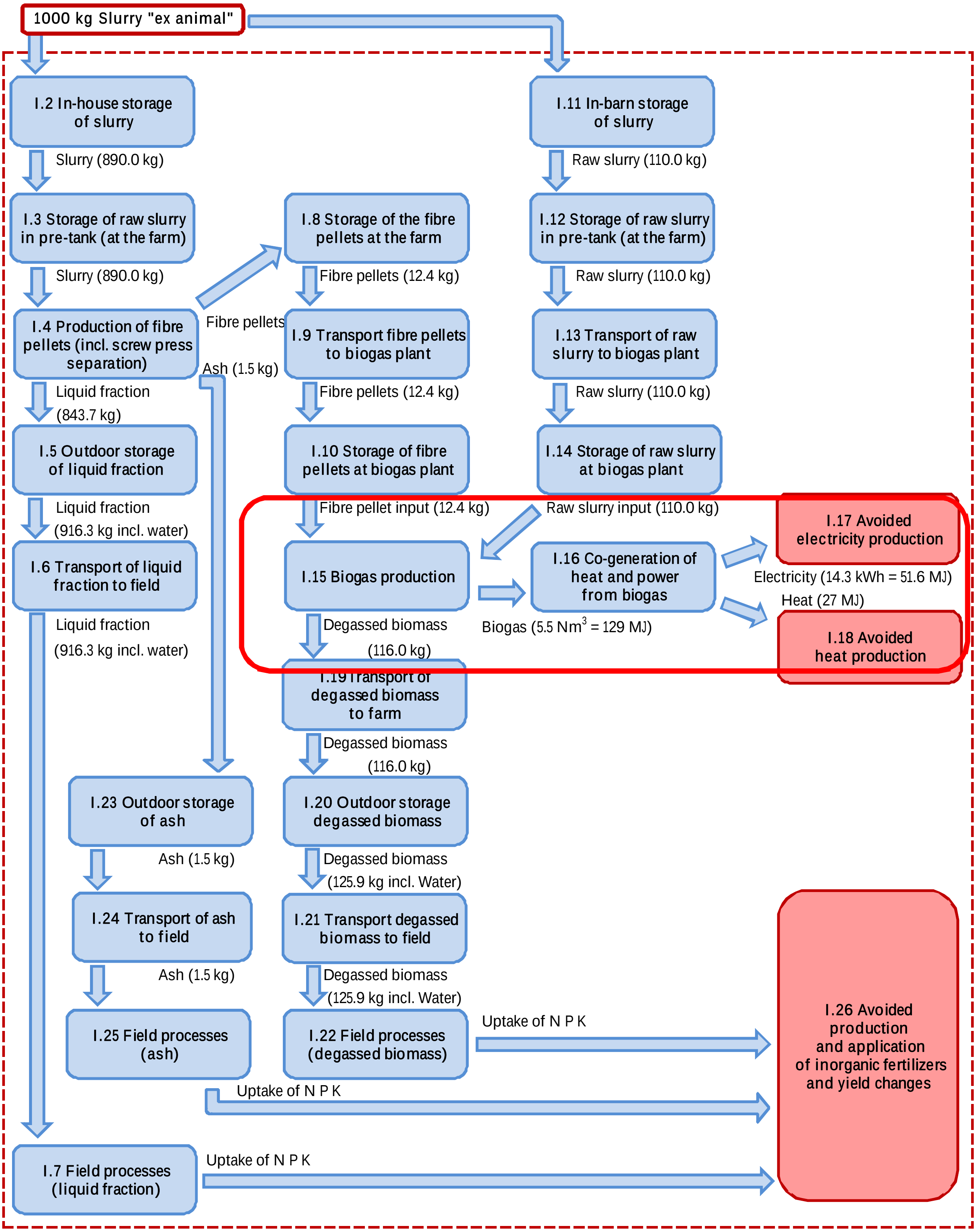
I.13 Transport of raw slurry to biogas plant

This process is identical to process H.13 from Annex H, see this.

I.14 Storage of the raw slurry at the biogas plant

This process is identical to process H.14 from Annex H, see this.

Processes I.15 to I.18: Biogas production, co-generation of heat and power and avoided heat and electricity production



I.15 Biogas production

I.15.1 Biogas principles

The principles for the biogas production in this annex is identical to the principles for the biogas production described in Annex F, see section F.15.1.

However, the composition of the biomass entering the biogas plants is changed. This is described in the following.

I.15.2 Biomass mixture entering the biogas plant

The biomass mixture input in the anaerobic digester is constituted of raw slurry (which composition is identical to the ex-housing pig slurry from table I.1) and fibre pellets (which composition is shown in table D.1 of Annex D). According to the composition and the degradability of both fractions, the amount of both fractions in the mixture is determined in order to obtain a biomass mixture that has a DM of approximately 10% during the digestion ***in the reactor,*** in order to obtain realistic production conditions (Jensen, 2009).

According to calculations provided by Xergi (Jensen, 2009), the 1000 kg mixture of the biomass entering the biogas plant consists of:

- 898.78 kg raw slurry (ex pre-tank)
- 101.22 kg fibre pellets

The mixture composition and mass balances is shown in table I.1 below.

Table I.1.
Mass balances for the biomass entering the biogas plant, i.e. a combination of fibre pellets and raw pig slurry (slurry from **fattening pigs**).

	Composition of the raw slurry a) [kg per 1000 kg slurry]	Composition of fibre pellets b) [kg per 1000 kg fibre pellets]	Mass balances			Composition of biomass entering the biogas plant c) [kg per 1000 kg biomass]
			Amount in untreated slurry [kg]	Amount in fibre pellets [kg]	Sum of mass [kg]	
Total mass	1000 kg	1000 kg	898.78 kg	101.22 kg	1000 kg	1000 kg
Dry matter (DM)	69.7 kg	889.3 kg	898.78 /1000 * 69.7 kg = 62.645 kg	101.22 /1000 * 889.3 kg =90.015 kg	152.66 kg	152.66 kg
Total-N	5.48 kg	11.75 kg	898.78 /1000 * 5.48 kg = 4.925 kg	101.22 /1000 * 11.75 kg = 1.189 kg	6.115 kg	6.115 kg
Total-P	1.13 kg	4.433 kg	898.78 /1000 * 1.13 kg = 1.016 kg	101.22 /1000 * 4.433 kg = 0.4487 kg	1.464 kg	1.464 kg
Potassium (K)	2.85 kg	3.563 kg	898.78 /1000 * 2.85 kg = 2.562 kg	101.22 /1000 * 3.563 kg = 0.361 kg	2.922 kg	2.922 kg
Carbon (C)	33.3 kg	424.88 kg	898.78 /1000 * 33.3 kg = 29.929 kg	101.22 /1000 * 424.88 kg = 43.006 kg	72.936 kg	72.936 kg
Copper (Cu)	0.03 kg	0.0595 kg	898.78 /1000 * 0.03 kg = 0.02696 kg	101.22 /1000 * 0.0595 kg =0.006023 kg	0.03299 kg	0.03299 kg
Zinc (Zn)	0.0894 kg	0.2428 kg	898.78 /1000 * 0.0894 kg = 0.08035 kg	101.22 /1000 * 0.2428 kg = 0.02458 kg	0.1049 kg	0.1049 kg

a) Same as in table A.1 (which is from ex-housing slurry in Annex A)
b) Same as in table D.1 from Annex D.
c) Composition of biomass mixture of slurry and fibre pellets entering the biogas plant, i.e. the biomass input into the digester

In this project, the functional unit is “Management of 1000 kg slurry ex-animal”. The biogas production therefore has to be related to the functional unit by the use of mass balances, i.e. the values expressed per 1000 kg of biomass mixture must be converted in order to be expressed per 1000 kg of slurry ex-animal. To do this, the amount of biomass mixture (898.78 kg raw slurry plus 101.22 kg fibre pellets) used per 1000 kg of slurry ex-animal must be calculated. This calculation can be done in 6 steps:

- ***Step 1: Defining the total amount of “ex-animal” slurry involved – contribution from the raw slurry input***
  The 898.78 kg raw slurry entering the biogas plant is “ex pre-tank ”, which corresponds to the same amount of “ex-animal” slurry, since it is assumed that no water was added during the storage in the pre-tank. Therefore, the amount of raw slurry ex-animal from this input is 898.78 kg.
- ***Step 2: Defining the total amount of “ex-animal” slurry involved – contribution from the input of fibre pellets***

The 101.22 kg of fibre pellets origins from 7272.07 kg slurry ex-housing (as 1000 kg raw slurry gives 13.919 kg fibre pellets, see section E.4 in Annex E) [2].

- ***Step 3: Defining the total amount of "ex-animal" slurry involved – sum of the two biomasses input***
  It means that a biomass mixture of 898.78 kg raw slurry + 101.22 kg fibre fraction origins from: 898.78 kg + 7272.07 kg = 8170.85 kg pig slurry ex-animal.
- ***Step 4: Relating the 898.78 kg of raw slurry input to the functional unit (1000 kg slurry ex-animal)***
  As the functional unit in this study is 1000 kg slurry ex-animal, the amount of "raw slurry for biogas mixture" is: 898.78 kg *1000 kg / 8170.85 kg = 109.998 kg raw slurry (ex pre-tank) per functional unit (1000 kg slurry ex-animal) (and 109.998 kg raw slurry ex pre-tank corresponds to 109.998 kg slurry ex-animal, as there is no water addition during the in-house storage).
- ***Step 5: Relating the 101.22 kg of fibre pellets input to the functional unit (1000 kg slurry ex-animal)***
  The amount of fibre fraction needed for the biogas mixture is: 101.22 kg *1000 kg / 8170.85 kg = 12.3879 kg fibre pellets per 1000 kg slurry ex-animal (and 12.388 kg fibre pellets corresponds to 890.002 kg pig slurry ex-animal [3]).
- ***Step 6: Total biomass input needed per functional unit***
  The biomass needed for the process is then 109.998 kg pig slurry (ex pre-tank) + 12.3879 kg fibre pellets = 122.386 kg "biomass mixture" entering the biogas plant per 1000 kg of slurry "ex-animal".

The mass flows in figure I.1 are based on the mass flows calculated above.

I.15.3 Energy consumption during biogas production and heat value of the biogas produced

The energy parameters for the biogas production are calculated using the same principles and calculation methods as in Annex F. However, there is one important difference: The specific methane yields for the fibre pellets is 187 Nm^3 per ton (170 Nm^3 per ton from primary digester + 10 % extra from secondary step), i.e. the same as for the fibre fraction in Annex H (the fibre fraction from the Samson Bimatech separation). These data are based on Møller (2007) (the same reference as used for the corresponding data in Annex F). The fibre fraction data used are those referred to as "solids from separation by mechanical equipment (solid 2, 3)" by Møller (2007).

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[2] According to the footnotes for table C.3 in Annex C, the separation of 1000 kg pig slurry gives 51.98 kg fibre fraction. From Annex D (table D.1) and the text for this, it can be seen that when 1000 kg of pig slurry undergoing mechanical separation and pellet production, 23.199 kg fibre pellets are produced. As described in section E.4, Annex E, 40% of the fibre pellets are used for drying the fibre pellets, i.e. the amount left is 23.199 kg fibre pellets * 60% = 13.919 kg fibre pellets.
Accordingly, in order to produce 101.22 kg fibre pellets for the biogas plant, 1000 kg pig slurry * 101.22 kg/13.919 kg = 7272.07 kg raw slurry is needed.

[3] 12.388 kg fibre pellets * (1000 kg slurry ex-animal / 13.919 kg fibre pellets) = 890.002 kg pig slurry ex-animal.

Accordingly, the data for the calculations are:

- The amount of VS corresponds to 80 % of DM.
- The specific methane yields for the untreated pig slurry is 319 Nm^3 per ton (290 Nm^3 per ton from primary digester + 10 % extra from secondary step)
- The specific methane yields for the fibre fraction is 187 Nm^3 per ton (170 Nm^3 per ton from primary digester + 10 % extra from secondary step).
- The biogas is constituted of 65 % CH_4 and 35 % CO_2 (table F.17 in Annex F).

The calculation principles are explained in Annex F and will not be repeated here. The results of the calculations are:

- A total of 45.31 Nm^3 biogas is produced per 1000 kg of "biomass mixture" [4].
- The biogas density being 1.158 kg/Nm^3, a mass of 52.47 kg of biogas per 1000 kg of "biomass mixture" is therefore produced.
- The heat value of the biogas corresponds to 1053.8 MJ per 1000 kg biomass mixture"[5].
- During the process, both heat and electricity are consumed. See further description in section F.15.3. The electricity therefore consumed for producing the biogas corresponds to 5.85 kWh per 1000 kg "biomass mixture"[6].
- The heat consumption for the process is 116.49 MJ per 1000 kg "biomass mixture" [7].

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[4] From pig slurry: 898.78 kg slurry* 69.7 kg DM/ 1000 kg slurry * 0.8 kg VS per kg DM * 319 Nm^3 CH_4 per ton VS / 0.65 Nm^3 CH_4 per Nm^3 biogas * ton/1000 kg = 24.60 Nm^3 biogas.

From fibre pellets: 101.22 kg fibre pellets * 889.3 kg DM/1000 kg fibre fraction * 0.8 kg VS per kg DM * 187 Nm^3 CH_4 per ton VS / 0.65 Nm^3 CH_4 per Nm^3 biogas * ton/1000 kg = 20.72 Nm^3 biogas.

Total biogas produced per 1000 kg of "biomass mixture": 45.31 Nm^3 biogas (24.60 Nm^3 from slurry + 20.72 Nm^3 from fibre fraction).

[5] This is calculated using the heat value and the total biogas produced: 6.46 kWh/Nm^3 biogas (see table F.19) * 45.31 Nm^3 biogas/1000 kg "biomass mixture" * 3.6 MJ/kWh = 1053.8 MJ/1000 kg "biomass mixture".

[6] Estimated internal consumption of electricity in kWh per 1000 kg biomass mixture : 45.31 Nm^3 biogas/1000 kg biomass mixture x 6.46 kWh/Nm^3 biogas x 40 % engine power efficiency x 5 % internal consumption = 5.85 kWh per 1000 kg biomass mixture.

[7] It is assumed that the average temperature for the biomass is 8 °C when entering the process and that it is heated to 37°C (the process temperature). Specific heat is calculated based on the content of DM and water (calculated as 1-DM), assuming that the specific heat for DM corresponds to 3.00 kJ/kg°C and to 4.20 kJ/kg°C for water. As the DM for biomass mixture is 152.66 kg/1000 kg biomass mixture (table I.6), it involves that the water content is 1000kg – 152.66 kg = 847.34 kg/1000 kg biomass mixture. The heat consumption for heating the biomass mixture from 8°C to 37°C is thus:

For DM: 152.66 kg DM/1000 kg biomass mixture * 3.00 kJ/kg DM*°C * (37-8) °C = 13281.4 kJ/1000 kg biomass mixture;

For water : 847.34 kg water/1000 kg biomass mixture * 4.20 kJ/kg DM*°C * (37-8) °C = 103206 kJ/1000 kg biomass mixture;

I.15.4 Emissions of CH_4 and CO_2

As the biogas plant is constructed tight in order to reduce losses of biogas, the emissions to air during the digestion are assumed to be rather small. As described in Annex F, section F.15.4, the emission of CH_4 from the biogas plant is estimated as 1% of the produced methane.

For the emissions of CO_2, Jungbluth et al. (2007) used an emission of 1 % of the produced carbon dioxide in the biogas. In this project, the calculated ratio between emissions of CO_2 and CH_4 in anaerobic conditions will be used, i.e. 1.42 kg CO_2 per kg CH_4 (see section F.5.5 in Annex F). This, in the present case, corresponds to 0.96 % of the CO_2 produced, which is in the same magnitude as proposed by Jungbluth et al. (2007).[8] .

I.15.5 Emissions of NH_3 and N_2O

As described in Annex F, section F.15.5, the emissions of NH_3 and N_2O from the biogas plant are assumed to be insignificant.

I.15.6 Life cycle data and mass balances for anaerobic digestion process

In this scenario, the biogas is not upgraded (which is necessary if it is going to be used as fuel for transport). The biogas is used for co-production of electricity and heat. Table I.2 presents the life cycle data for the anaerobic digestion process.

Total: (13281.4 kJ + 103206 kJ) kJ/1000 kg biomass mixture * MJ/1000 kJ = 116.49 MJ/1000 kg biomass mixture.

[8] When calculating in accordance with the biogas composition, which is defined as 65% CH_4 and 35% CO_2 (see table F.19 in Annex F), then the ratio is 1.477 kg CO_2 per kg CH_4: 0.65 mol CH_4-C corresponds to 0.35 mol CO_2-C i.e.
1 mol CH_4-C gives 0.538 mol CO_2-C (= 0.35/0.65)
Accordingly: 16.04276 g CH_4/mol = 0.538 * 44.0098 g CO_2/mol
i.e. 1 g CH_4 = 1.477 g CO_2
1.42/1.477 = 96%

Table I.2.
Life cycle data for the anaerobic digestion process. Data per 1000 kg biomass mixture into the biogas plant.

	Biomass mixture	Comments
Input		
Biomass mixture	1000 kg	All emissions are calculated relatively to 1000 kg "biomass mixture" (i.e. 89.88% raw slurry and 10.12% fibre pellets)
Output		
Biogas	52.47 kg i.e. 45.31 Nm^3	Density 1.158 kg/Nm^3, see text.
Degassed slurry	947.53 kg	Gas output is dried. No water loss. Therefore, the only loss is the mass of the biogas : 1000 kg – 52.47 kg= 947.53 kg
Energy consumption		
Electricity	5.85 kWh	Estimated own consumption of electricity: 5 % of net production, engine efficiency of 40 %, see text. Electricity from the grid.
Heat	116.49 MJ	Heating the biomass from 8°C to 37°C, see text. Heat from the co-generation unit.
Emissions to air		
Carbon dioxide (CO_2)	0.314 kg	1.42 kg CO2 per kg CH4. 0.211 kg CH4 * 1.42 kg CO2 per kg CH4.= 0.314 kg CO2
Methane (CH_4)	0.211 kg	1% of the methane content of the biogas is assumed to be emitted to the environment. 45.31 Nm^3 biogas * 65% CH4 * 0.717 kg/Nm^3 * 1% = 0.211 kg CH4.
Ammonia (NH_3-N)		Assumed to be insignificant, see text
Nitrous oxide (N_2O-N)		Assumed to be insignificant, see text
Nitrogen oxides (NO_X)		Assumed to be insignificant, see text
Nitrogen monoxide(NO)		Assumed to be insignificant, see text
Nitrogen(N_2)		Assumed to be insignificant, see text
Hydrogen sulphide (H_2S)		Assumed to be insignificant compared to the emissions from the following co-production of electricity and heat.
Odour		No data
Emissions to water		
		No emissions to water
Emissions to soil		
		No emissions to soil

The composition of the degassed slurry after biogas production is shown in table I.3. It is based on mass balances from data presented in table I.2 for the total mass, the DM content and the total N.

Table I.3.
Mass balances for the biogas mixture before and after the biogas plant

	Composition of Mixture of slurry and fibre pellets entering the biogas plant [kg per 1000 kg biomass mixture]	Mass balance: Change during biogas production [kg]	Mass balance: Amount after biogas production [kg]	Composition of Degassed biomass after biogas production a) [kg per 1000 kg degassed biomass]
Total mass	1000 kg	- 52.47 kg b)	947.53 kg	1000 kg
Dry matter (DM)	152.66 kg	- 52.47 kg c)	100.19 kg	105.74 kg
Total-N	6.115 kg	No change	6.115 kg	6.4533 kg
Total-P	1.464 kg	No change	1.464 kg	1.5454 kg
Potassium (K)	2.922 kg	No change	2.922 kg	3.0840 kg
Carbon (C)	72.936 kg	- 24.61 kg d)	48.322 kg	50.9975 kg
Copper (Cu)	0.03299 kg	No change	0.03299 kg	0.0348 kg
Zinc (Zn)	0.1049 kg	No change	0.1049 kg	0.1107 kg

a) All the data are the same as in the precedent column, but adjusted to be expressed per 1000 kg of degassed mixture, instead of per 947.53 kg of degassed mixture.
b) This loss corresponds to the biogas produced, expressed in mass terms.
c) No water loss and therefore change in dry matter is equal to change in total mass.
d) This corresponds to the losses in the biogas itself and the losses that occurred during the digestion process:
Losses in the biogas are calculated as the sum of CH_4-C and CO_2-C: (45.31 Nm^3 biogas * 65 % CH_4 * 0.717 kg CH_4/Nm^3) * (12.011 g/mol /16.04 g/mol) + (45.31 Nm^3 biogas * 35 % CO_2 * 1.977 kg CO_2/Nm^3) * (12.011 g/mol /44.01 g/mol) = 24.4 kg C
Losses from the digestion process are the aggregated losses as CO_2-C + CH_4-C: 0.313 kg CO_2 * (12.011 g/mol /44.01 g/mol) + 0.211 kg CH_4 * (12.011 g/mol /16.04 g/mol) = 0.24 kg C
Total C loss : 23.2 kg C + 0.23 kg C = 24.6 kg C.

I.15.7 Material consumption for the anaerobic digestion plant

The materials for the anaerobic digestion plant are identical to the material consumption for the anaerobic digester in Annex F, section F.15.7, see this.

I.16 Co-generation of heat and power from biogas

Also in this annex it is assumed that the biogas produced is used for the production of electricity and heat. The technology and basic methods for calculations are the same as in Annex F, however, the biogas production per 1000 kg slurry “ex-animal” is somewhat different.

As detailed in section I.15.3, the system produces 45.31 Nm^3 biogas per 1000 kg of biomass mixture. As there are 122.386 kg biomass mixture per 1000 kg slurry ex-animal (see detailed calculation in section I.15.2), this corresponds to a production of 5.545 Nm^3 biogas per 1000 kg slurry ex-animal[9].

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[9] 122.386 kg biomass mixture (per 1000 kg slurry ex-animal) * 45.31 Nm^3 / 1000 kg biomass mixture = 5.545 Nm^3 biogas per 1000 kg slurry ex-animal.

The net energy production after the co-generation unit is therefore 59.3 MJ heat plus 14.33 kWh electricity (51.59 MJ) per 1000 kg slurry ex-animal[10].

As also detailed in section I.15.3, some of the produced heat is used to fulfil the heat demand of the biogas production. The amount of heat needed for this purpose is 116.49 MJ per 1000 kg mixture input, which corresponds to 14.257 MJ per 1000 kg slurry ex-animal[11]. The heat consumption by the biogas plant thus corresponds to 14.257 MJ/ 59.329 MJ = 24.0 % of the heat produced. The surplus heat for the system is 59.329 MJ – 14.257 MJ = 45.072 MJ for the total system.

As described in Annex F (section F.16), it is considered that only 60 % of the surplus heat produced at the biogas plant is used, the remaining 40 % being wasted. Therefore, out of the 45.072 MJ per 1000 kg slurry ex-animal of net surplus heat, only 27.04 MJ (i.e. 45.072 MJ * 60%) are used to fulfil the heat demand. The wasted heat thus corresponds to 18.0 MJ.

The energy produced from the biogas can be summarized as:

- 14.33 kWh electricity (51.59 MJ) per 1000 kg slurry ex-animal, all used through the national electricity grid, low voltage electricity.
- 59.3 MJ heat per 1000 kg slurry ex-animal, of which:
    - 14.257 MJ per 1000 kg slurry ex-animal is used for fulfilling the heat demand of the biogas process itself;
    - 27.04 MJ per 1000 kg slurry ex-animal is used to fulfil national heat demand;
    - 18.0 MJ per 1000 kg slurry ex-animal is wasted.

As for Annex F, the emissions from the biogas engine were estimated from recent data from the Danish National Environmental Research Institute (DMU, 2009) (plants in agriculture, combustion of biogas from stationary engines).

Table I.4 presents the life cycle data related to the co-generation of heat and power from the biogas engine.

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[10] Heat produced: 5.545 Nm^3 biogas (per 1000 kg slurry ex-animal) * 23.26 MJ/ Nm^3 biogas (heat value of the biogas, see table F.19 in Annex F) * 0.46 (engine efficiency for heat) = 59.329 MJ heat per 1000 kg slurry ex-animal.
Electricity produced: 5.545 Nm^3 biogas (per 1000 kg slurry ex-animal) * 23.26 MJ/ Nm^3 biogas (heat value) * 0.40 (engine efficiency for electricity) = 51.59 MJ electricity per 1000 kg slurry ex-animal. This corresponds to 51.59 MJ * MJ/3.6 kWh = 14.33 kWh electricity per 1000 kg slurry ex-animal.

[11] There is 122.386 kg biomass mixture per 1000 kg slurry ex-animal, see section I.15.2. The heat required for the process is 116.49 MJ per 1000 kg mixture (section I.15.3). The heat needed per functional unit corresponds to: 122.386 kg biomass mixture / 1000 kg slurry ex-animal * 116.49 MJ / 1000 kg biomass mixture = 14.257 MJ per 1000 kg slurry ex-animal.

Table I.4.
Life cycle data for the co-generation of heat and power from biogas. Data per 1 MJ energy input.

	Per MJ input	Comments
Input		
Biogas	0.043 Nm^3 (1 MJ)	Amount of biogas corresponding to an energy content of 1 MJ input.[1 MJ/23.26 MJ/Nm^3] = 0.043 Nm^3.
Co-generation unit	5.0 E-9 p	Engine, generator, electric parts etc. divided by lifetime (Data from Jungbluth et al., 2007, table 13.20 of page 259)
Lubricating oil	3.0 E-5 kg	Production and disposal of used mineral oil included (Data from Jungbluth et al., 2007, table 13.20 of page 259)
Output		
Heat	0.46 MJ	The efficiency of the heat production is 46% (see table I.17)
Of this: Used for biogas plant	0.110 MJ	The heat consumption used by the biogas plant is 24.0 % : 0.46 MJ * 24.0 % = 0.110 MJ.
Surplus heat	0.35 MJ	Surplus heat: 0.46 MJ – 0.110 MJ = 0.35 MJ
Electricity	0.40 MJ	The electricity efficiency is 40% (see Annex F, table I.19)
Emissions to air		
Carbon dioxide (CO_2)	8.36 E-2 kg	DMU (2009)
Carbon monoxide (CO)	2.73 E-4 kg	DMU (2009)
Methane (CH_4)	3.23 E-4 kg	DMU (2009)
Non-methane volatile organic compounds (NMVOC)	1.40 E-5 kg	DMU (2009)
Ammonia (NH_3-N)		No data
Nitrous oxide (N_2O)	1.59 E-7 kg	DMU (2009)
Nitrogen oxides (NO_X)	5.40 E-4 kg	DMU (2009)
Nitrogen monoxide(NO)		No data
Nitrogen(N_2)		No data
Particulates		DMU (2009)
PM_{10}	4.51 E-7 kg	
$PM_{2.5}$	2.06 E-7 kg	
Hydrogen sulphide (H_2S)		No data
Sulphur dioxide (SO_2)	1.92 E-5 kg	DMU (2009)
NMVOC	1.40 E-5 kg	DMU (2009)
Odour		No data
Emissions to water		
		No emissions to water
Emissions to soil		
		No emissions to soil

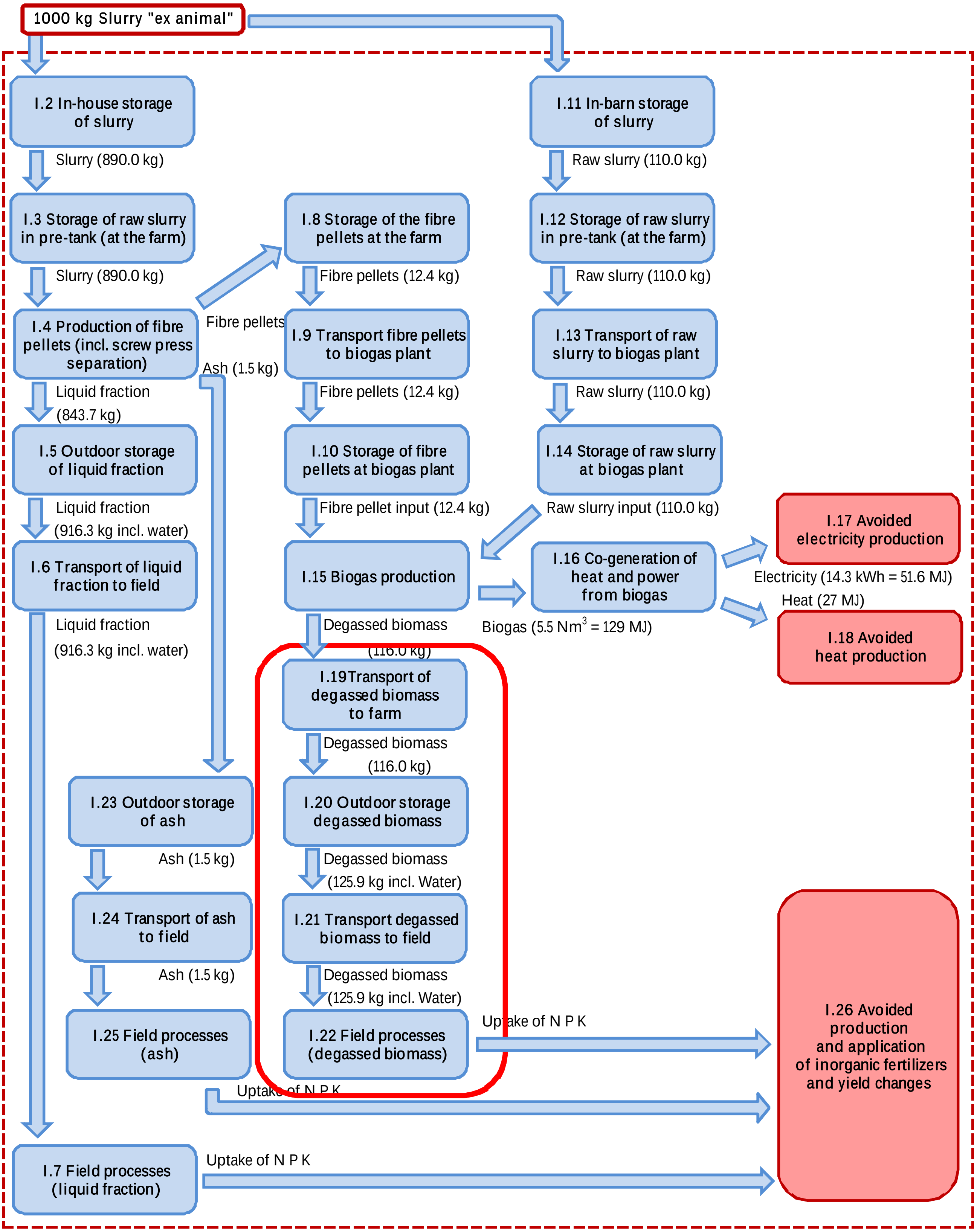
I.17 Avoided electricity production

The electricity that is replaced is the marginal electricity as described in Annex A, following the same principles as in Annex F, see section F.17. However, the amounts of replaced electricity are different than in Annex F.

I.18 Avoided heat production

The avoided heat production is described in Annex F, section F.18. However, the amounts of replaced heat are different than in Annex F.

Processes I.19 to I.22: Fate of the degassed biomass



I.19 Transport of the degassed biomass to the farm

The transport of the degassed biomass to the farm is identical to the process from Annex F, “Transport of the degassed liquid fraction” – except that the amount is different. Accordingly, the transport distance is 5 km.

I.20 Outdoor storage of the degassed biomass

I.20.1 General description

The outdoor storage of the degassed biomass is assumed to be mostly identical to the outdoor storage of the reference slurry in Annex A, including some adjustments in order to take the “degassed” perspective into account.

The degassed biomass is thus stored in an outdoor concrete tank covered with a floating layer consisting of 2.5 kg of straw per 1000 kg slurry stored. As in section I.5.1, the life cycle data of straw production are not included in this study, as straw is regarded as a waste product from cereal production (rather than a co-product).

I.20.2 Addition of water

The degassed biomass will be diluted by precipitation in the same amount as described in I.5.2, i.e. a total of 86 kg of water.

I.20.3 Electricity consumption

It is assumed that the electricity consumption is identical to the electricity consumption for the storage of the reference slurry in Annex A. Accordingly, the electricity for pumping and stirring is taken from table A.10 (Annex A).

The electricity consumption thus involves : the consumption for stirring when straw is added (1.2 kWh per 1000 kg slurry), the consumption for stirring (1.2 kWh per 1000 kg slurry) and pumping (0.5 kWh per 1000 kg slurry), before application to the field. This gives an electricity consumption of 2.9 kWh per 1000 kg slurry.

Note, that for the liquid fraction in section I.5.3, the energy consumption is adjusted by a reduction of 50 %, in order to account for the fact that the liquid fraction will offer less resistance during the pumping and stirring than does the raw slurry. As the degassed fibre fraction has a DM content (105.74 kg DM per kg degassed biomass, see table I.8) that is even higher than the DM content of the reference slurry “ex-housing” (69.7 kg DM per kg slurry “ex-housing”, see table A.1 in Annex A), the energy consumption for pumping and stirring has not been reduced.

I.20.4 Emissions of CH_4

It has not been possible to find high quality data about the CH_4 emissions occurring during the storage of degassed biomass. Yet, in the latest Danish national inventory report for greenhouse gases, Nielsen et al. (2009) calculated the absolute CH_4 reduction of biogas-treated slurry by using the

IPCC methodology[12], coupled with a reduction potential factor of 50 % in the case of pig slurry. When applying this equation, Nielsen et al. (2009) considered the VS content of the treated slurry instead of the VS content ex-animal.

This is the methodology that will be applied in this project. The VS is estimated as 80% of the DM content. This corresponds to a VS content of 84.592 kg per 1000 kg degassed biomass (= 80% of the 105.74 kg DM per 1000 kg degassed biomass from table I.8). As regarding the reduction potential factor, in this project, the interest is not the reduction, but the emissions occurring, so a factor of (100 – 50 %) will be used instead of 50 % (which in this case does not change anything mathematically).

The CH_4 emissions are therefore calculated as: 84.592 kg VS/1000 kg degassed biomass * 0.45 m^3 CH_4/kg VS * 0.67 kg CH_4/m^3 CH_4 * 10% * (100-50) % = 1.275 kg CH_4/1000 kg degassed biomass.

I.20.5 Emissions of CO_2

Emissions of CO_2 were estimated with the calculated ratio between emissions of CO_2 and CH_4 in anaerobic conditions, i.e. 1.42 kg CO_2 per kg CH_4 (see Annex F, section F.5.5). As mentioned in section F.5.5, part of the produced CO_2 from the outdoor storage is emitted to air immediately and part of the CO_2 is dissolved in the slurry. However, in this life cycle assessment, it is calculated as all the CO_2 is emitted to air immediately, which makes the interpretation of the sources easier, as detailed in section I.2.

This gives a CO_2 emission of 1.42 kg CO_2 per kg CH_4 * 1.275 kg CH_4/1000 kg degassed biomass = 1.811 kg CO_2.

I.20.6 Emissions of NH_3

Hansen et al. (2008) states that there are no clear differences between the ammonia (NH_3) emissions from degassed slurry and untreated slurry. On one hand, the lower content of dry matter might reduce the emission of ammonia, on the other hand, TAN concentration and pH of degassed slurry are higher, which both increase the potential for ammonia emissions. Yet, Sommer (1997), who measured the NH_3 volatilization from both covered (one tank covered by straw and one tank covered by clay granules) and uncovered storage tank containing digested slurry, concluded that ammonia volatilization from the covered slurry was insignificant.

The ammonia emissions occurring during the storage of the degassed biomass are therefore calculated using the same assumptions as for the reference scenario, i.e. the emission of NH_3–N are 2% of the total-N, based on Poulsen et al. (2001). The total N being 5.716 kg N/1000 kg degassed biomass, the NH_3-N emissions are 0.114 kg NH_3-N per 1000 kg degassed biomass.

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[12] According to IPCC (2006), the methane emission can be calculated as:
CH_4 [kg] = VS [kg] * B_0 * 0.67 [kg CH_4 per m^3 CH_4] * MCF
B_0 = 0.45 m^3 CH_4 per kg VS for market swine (IPCC, 2006, Table 10A-7). The MCF value used is 10 % (for liquid slurry with natural crust cover, cool climate, in table 10-17 of IPCC (2006)). This is also the MCF recommended under Danish conditions by Nielsen et al. (2009).

I.20.7 Emissions of N_2O, NO-N and N_2-N

In the reference scenario, the direct N_2O emissions for storage were based on IPCC guidelines (IPCC, 2006). However, the IPCC methodology does not provide any emission factor for storage of degassed biomass. The fact that the biomass is degassed involves a reduction in the N_2Oemissions, as part of the most easily converted dry matter was removed during the biogas production (Mikkelsen et al., 2006).

Yet, as for the CH_4 emissions, the latest Danish national inventory report for greenhouse gases (Nielsen et al., 2009) considered a reduction potential factor for estimating the reductions in N_2O-N emissions obtained when the slurry is biogas-treated. In the case of pig slurry, this reduction potential factor is 40 %.

In the present project, the direct N_2O-N emissions will be estimated as in section I.5.7 (i.e. relatively to the emissions in the reference scenario but adjusted with the different N content), and this result will be multiplied by (100-40) % in order to consider the fact that the biomass is degassed.

The direct N_2O-N emissions are therefore calculated as: 0.033 kg N_2O-N/1000 kg slurry ex-housing * (5.716 kg N in 1000 kg of degassed biomass/ 5.48 kg N in 1000 kg slurry ex-housing) * (100-40) % = 0.02065 kg N_2O-N/1000 kg degassed biomass.

The NO-N and N_2-N emissions were calculated in the same way as in Annex A, i.e. based on the study of Dämmgen and Hutchings (2008). In their study, they assumed that the emission of nitrogen monoxide (NO) is the same as the direct emission of nitrous oxide (N_2O) (measured as NO-N and N_2O-N). Furthermore, they assumed that emission of nitrogen (N_2) is three times as high as the direct emissions of nitrous oxide (N_2O) (measured as N_2-N and N_2O-N).

As regarding the total NO_x emissions ($NO_x = NO + NO_2$), it was assumed, as in Annex A, that $NO_x = NO$. This is because it has not been possible to find data on NO_2.

Therefore, this means that the NO-N emissions (and thereby the NO_x-N emissions) correspond to 0.02065 kg N_2O-N per 1000 kg degassed biomass, and the N_2-N emissions correspond to 0.06196 kg per 1000 kg degassed biomass.

The indirect N_2O-N emissions can be calculated as described by IPCC guidelines (IPCC, 2006), i.e. as 0.01 * (NH_3-N + NO_x-N). This gives indirect N_2O-N emissions of 0.001347 kg per 1000 kg degassed biomass.

I.20.8 Life cycle data and mass balances for storage of degassed biomass

Table I.5 summarizes the life cycle inventory data for the storage of the degassed biomass and presents the comparison with the storage emissions in Annex A. It must be emphasized that 1000 kg of degassed biomass do ***not*** correspond to 1000 kg slurry ex-animal, so the values of Annex A versus

Annex I are not directly comparable. Values from Annex A were only included since they were needed for the calculation of some of the emissions.

Table I.6 presents the mass balances of the degassed slurry in order to establish its composition after the storage. In this table, it can be noticed that the change of DM is estimated as the losses of N and C. It is acknowledged that this is a rough estimation, as other elements of greater molecular weight may also be lost (e.g. dissolved O_2). The estimated DM change shall therefore be seen as a minimum change, the actual DM change may in fact be greater than the one taken into account in this study.

Table I.5
Life cycle data for storage of the degassed biomass. All data per 1000 kg of degassed biomass “ex-biogas plant”.

	Reference pig slurry (scenario A)	Degassed biomass (fattening pig slurry) (scenario I)	Comments
Input			
Degassed biomass “ex-biogas plant”		1000 kg	The emissions are calculated relative to this.
Slurry “ex-housing”	1000 kg		
Water	86 kg	86 kg	
Concrete slurry store	Included	Included	As in scenario A.
Cut straw	2.5 kg	2.5 kg	As straw is regarded as a waste product from cereal production (rather than a co-product), the life cycle data of straw production is not included.
Output			
Slurry/degassed biomass “ex-storage”	1086 kg	1086 kg	
Energy consumption			
Electricity		2.9 kWh	Electricity for pumping and stirring, see text.
Emissions to air			
Carbon dioxide (CO_2)	0.18 kg (New 2.755 kg)	1.8108 kg	Calculated from CH_4 emissions: kg CO_2 = kg CH_4 * 1.42 (see text).
Methane (CH_4)	1.94 kg	1.2752 kg	IPCC methodology with the VS content in the biomass, and with a reduction factor of 50 % (see text): 84.592 kg VS/1000 kg degassed biomass * 0.45 m^3 CH4/kg VS * 0.67 kg CH4/m^3 CH4 * 10% * (100-50) % = 1.2752 kg CH4/1000 kg degassed biomass.
Ammonia (NH_3-N)	0.11 kg	0.129 kg	NH_3-N = 2% of the total-N in the degassed biomass “ex-separation”, see text.
Direct emissions of Nitrous oxide (N_2O-N)	0.033 kg	0.02332 kg	Estimation based on the emissions in the reference scenario, but adjusted with the relative N content. A reduction factor of 40 % was considered (see text): 0.033 kg *(5.716kg N in 1000 kg of degassed biomass/ 5.48 kg N in 1000 kg slurry ex-housing) * (100-40) % = 0.02332 kg N2O-N/1000 kg degassed biomass.
Indirect emissions of Nitrous oxide (N_2O-N)	0.00143 kg	0.001524 kg	0.01 kg N_2O–N per kg (NH_3–N + NO_X–N) volatilised (IPCC, 2006, table 11.3), see text.
Nitrogen monoxide (NO-N) (representing total NO_X)	0.033 kg	0.02332 kg	Estimate based on Dämmgen and Hutchings (2008), consisting of assuming that NO-N = (direct) N_2O-N * 1, see text.
Nitrogen dioxide (NO_2-N)	No data	No data	No data
Nitrogen (N_2-N)	0.099 kg	0.06995 kg	Estimate based on Dämmgen and Hutchings (2008), consisting of assuming that N_2-N = (direct) N_2O-N * 3.
Discharges to water			
	None	None	Assumed to be none, as leakages from slurry tanks are prohibited in Denmark

Table I.6.
Mass balances for storage of degassed biomass

	Composition of degassed biomass AFTER biogas plant and BEFORE storage (from table I.8) [kg per 1000 kg degassed biomass]	Mass balance: Change during storage of degassed biomass [kg]	Mass balance: Amount after storage of degassed biomass [kg]	Composition of degassed biomass AFTER storage [kg per 1000 kg degassed biomass AFTER storage]
Total mass	1000 kg	86 kg	1086 kg	1000 kg
Dry matter (DM)	105.74 kg	- 1.695 kg c)	104.04 kg	95.802 kg
Total-N	6.4533 kg	- 0.2456 kg a)	6.208 kg	5.716 kg
Total-P	1.5454 kg	No change	1.5454 kg	1.423 kg
Potassium (K)	3.0840 kg	No change	3.0840 kg	2.8398 kg
Carbon (C)	50.9975 kg	- 1.449 kg b)	49.55 kg	45.6247 kg
Copper (Cu)	0.0348 kg	No change	0.0348 kg	0.0321 kg
Zinc (Zn)	0.1107 kg	No change	0.1107 kg	0.1020 kg

[a] Changes in total N: 0.129 kg NH_3-N + 0.02332 kg N_2O-N + 0.02332 kg NO-N + 0.06995 kg N_2-N = 0.2456 kg N

[b] Changes in total C: 1.8108 kg CO2 * 12.011 [g/mol] /44.01 [g/mol] + 1.2752 kg CH4 * 12.011 [g/mol] /16.04 [g/mol] = 1.4491 kg C

[c] The change in DM is assumed to be identical to the sum of the loss of N and C

I.21 Transport of degassed biomass to field

The transport of the degassed biomass to the field is identical to the process described in section F.6 (transport of the liquid fraction to the field).

I.22 Field processes for degassed biomass

I.22.1 General description

The field processes for the degassed biomass is assumed to be mostly identical to the field processes for the reference slurry in Annex A, including some adjustments in order to take the “degassed” perspective into account.

As in the process described in section F.7 (field processes for liquid fraction), the data from the Ecoinvent process “Slurry spreading, by vacuum tanker” (Nemecek and Kägi, 2007, p. 198) were used for the emissions related to spreading equipment “consumption”. This includes the construction of the tractor and the slurry tanker, as well as the diesel consumption. The diesel consumption due to the use of the “tanker” in the Ecoinvent process was adjusted to 0.4 litres of diesel per 1000 kg of slurry, based on Kjelddal (2009) (the same as in Annex A).

I.22.2 Emission of CH_4 and CO_2

The CH_4 emissions on the field are assumed to be negligible, as the formation of CH_4 requires an anaerobic environment, which is, under normal conditions, not the case in the top soil.

CO_2 emissions are modelled by the dynamic soil organic matter model C-TOOL (Petersen et al., 2002; Gyldenkærne et al., 2007). The development in organic soil N is modelled by assuming a 10:1 ratio in the C to N development.

I.22.3 Emissions of NH_3

Since the degassed biomass is subjected to both increasing and reducing factors as regarding the ammonia emission potential, the ammonia emissions were calculated as in the reference scenario. This is further detailed in section F.7.3 in Annex F (but without the 50% reduction factor as this reduction factor only applies for liquid fractions, and as the degassed biomass is not separated).

Accordingly, the NH_3-N emissions for the period after application are calculated by using the same method as used in section F.7.3 (but without the 50% reduction factor).

I.22.4 Emissions of N_2O and NO_X-N

The direct N_2O emissions are generally assumed to be smaller for degassed slurry than for untreated slurry (Sommer et al. 2001). This is because digested manure contains less easily decomposed organic matter than undigested manure (Börjesson and Berglund, 2007) and because more N is in a form already available to the plants (NH_4^+). This means that less N shall be available to microorganisms for nitrification (where NO_3^- is formed), and thus, the potential for denitrification (where NO_3^- is reduced to N_2O, and subsequently to N_2) is also reduced. This is also in accordance with Marcato et al. (2009), who concluded from their results that there are fewer risks for oxygen competition between the crops and soil bacteria (and therefore of N_2O emissions) with digested slurry as compared to undigested slurry. According to Sommer et al. (2001, table 2) N_2O emissions with degassed slurry are in the magnitude of 0.4 % of the applied N. Based on Sommer et al. (2001), Nielsen (2002) used, for field emissions with digested slurry, a reduction corresponding to 41 % of the emissions with raw slurry (i.e. from 34 to 20 g N_2O/ton manure) and Börjesson and Berglund (2007) assumed a reduction of 37.5 % (i.e. from 40 to 25 g N_2O per tonne of manure).

In this project, the estimate of Sommer et al. (2001) for digested slurry will be used as the best available data. This should be regarded as a rather rough estimate. A more precise value for the magnitude of this value would require either an adequate number of scientific based field measurements or detailed modelling in an appropriate tool, which has been beyond the frame of this project.

As in section F.7, indirect N_2O emissions ***due to ammonia and*** $\boldsymbol{NO_x}$ are evaluated as 0.01 kg N_2O-N per kg of (NH_3 + NO_x) volatilized. The indirect N_2O-N emissions ***due to nitrate leaching*** correspond to 0.0075 kg N_2O-N per kg of N leaching. The emissions of NO_X-N are calculated as 0.1* direct N_2O-N, based on Nemecek and Kägi (2007).

I.22.5 Emissions of N_2-N

The N_2-N emissions are based on the estimates from SimDen (Vinther, 2004). For soil type JB3 the N_2-N:N_2O-N ratio is 3:1 and for soil type JB6 the N_2-N:N_2O-N ratio is 6.

I.22.6 Calculation of degassed biomass fertilizer value

The calculation of the fertilizer value is presented on section I.26.

I.22.7 Nitrate leaching

The C/N ratio of the degassed biomass is higher than for raw pig slurry. Hence, a simplifying approach is used: the N “remaining” after gaseous losses and incorporation in the soil N pool is assumed to be divided between harvest and leaching in the same proportion as for pig slurry. See Annex F, section F.23.7 for further description. After the gaseous losses (table I.7), there is 3.7746 (JB3) and 3.5462 (JB6) kg N left for harvest and leaching. For the 100 years values, there is, after the gaseous losses, 5.4155 (JB3) and 5.4007 (JB6) kg N left for harvest and leaching.

I.22.8 Phosphorus leaching

For P leaching, the same assumptions as those used in Annex A were used, i.e., 10% of the P applied to field has the possibility of leaching and 6% of this actually reach the aquatic recipients, based on Hauschild and Potting (2005).

I.22.9 Cu and Zn fate

As in Annex A, it is considered that the entirety of the Cu and Zn applied will leach through the water compartment.

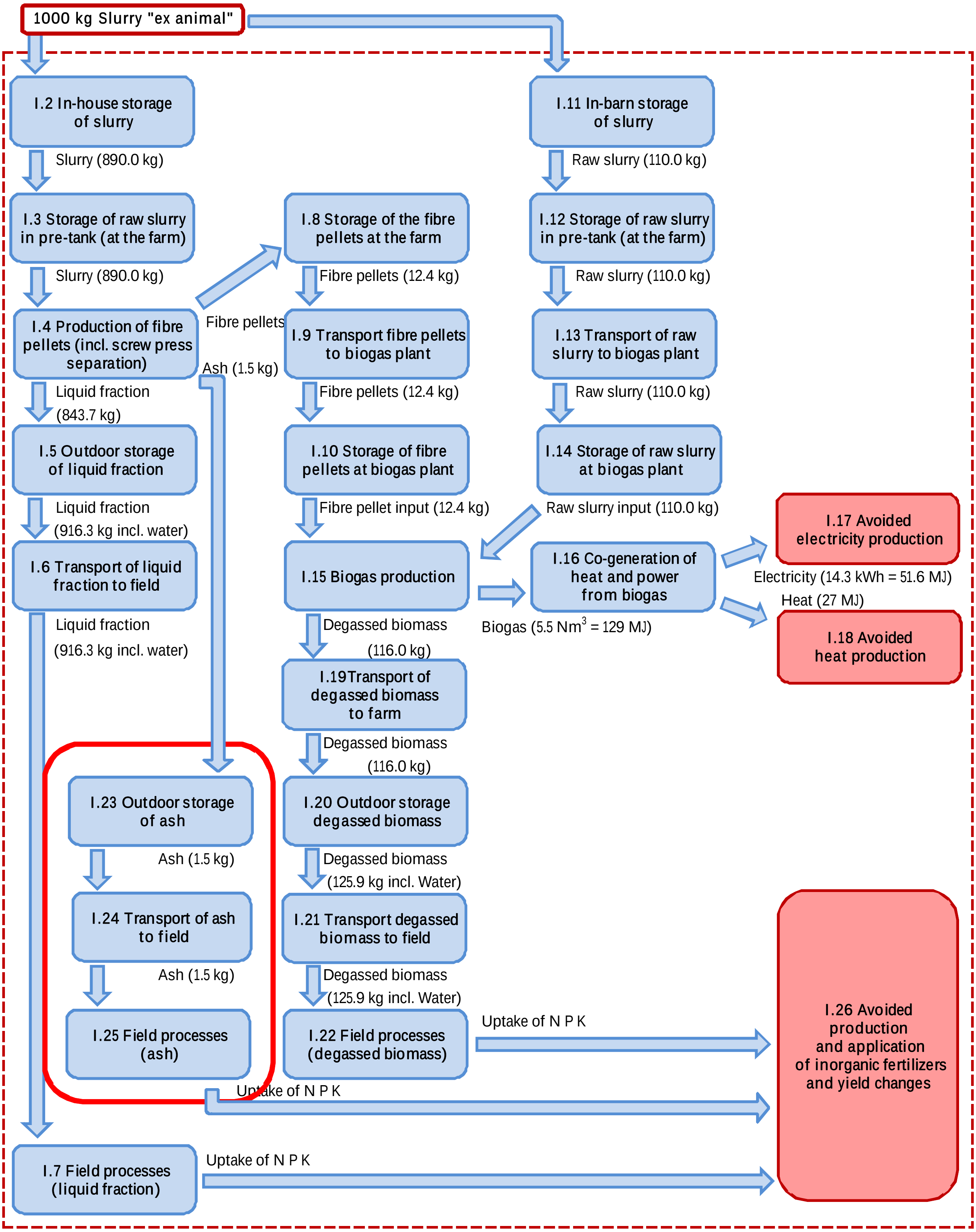
I.22.10 Life cycle data for field application of degassed biomass “ex-storage”

Table I.7 presents the life cycle data for the application of degassed biomass “ex-storage” on the field. The results of the reference case (Annex A) are also presented for comparison purposes. However, in order to be comparable, both results must be related to the functional unit, i.e. 1000 kg slurry ex-animal.

Table I.7.
Life cycle data for application of degassed biomass and field processes. All data per 1000 kg of "degassed biomass ex-outdoor storage".

	Fattening pig slurry	Degassed biomass ex-storage	Comments
Input			
Slurry/ degassed biomass "ex-storage"	1000 kg	1000 kg	Slurry / degassed biomass from the outdoor storage. This is the reference amount of slurry, i.e. the emissions are calculated relative to this.
Output			
Slurry on field, fertiliser value	See section A.6.1.	See section I.26	
Energy consumption			
Diesel for slurry	0.4 litres of diesel	0.4 litres of diesel	See Annex A.
Emissions to air			
Carbon dioxide (CO_2) Soil JB3 Soil JB6	 81.6 kg 80.2 kg	 127.6 (156.2) kg 125.3 (155.6) kg	Modelled by C-TOOL (Gyldenkærne et al, 2007). 10 year value.
Methane (CH_4)	Negligible	Negligible	Negligible, see Annex A.
Ammonia (NH_3-N) during application	0.02 kg	0.02258 kg	NH3 emissions during application: 0.5% of NH4+-N "ex-storage", the NH4+-N "ex-storage" being evaluated as 79 % of total N. 5.716 kg N * 79% * 0.5% = 0.02258 kg NH_3-N
Ammonia (NH_3-N) in period after application	0.48 kg	0.6006 kg	Correspond to 0.138 kg NH_3-N per kg NH_4^+-N in the degassed biomass (minus the NH3 emissions from application above). 5.716 kg N * 0.138 kg NH_3-N/kg TAN-N * 79% MINUS the 0.02258 kg NH_3-N from above = 0.6006 kg NH_3-N
Direct emissions of Nitrous oxide (N_2O-N)	0.05 kg [0.015-0.15]	0.0572 kg	0.01 [0.003 - 0.03] kg N_2O-N per kg N "ex-storage" for application of animal wastes to soil, based on IPPC (IPCC, 2006; table 11.1).
Indirect emissions of Nitrous oxide (N_2O-N) Soil JB3 Soil JB6	0.005 kg 0.014 kg 0.011 kg	0.00629 kg 0.01508 (0.01913) kg 0.0114 (0.01508) kg	Indirect emissions due to emissions of ammonia and NO_X: 0.01 kg N_2O–N per kg (NH_3–N + NO_X–N) volatilised (IPCC, 2006) Indirect emissions due to nitrate leaching: 0.0075 kg N_2O–N per kg N leaching (IPCC, 2006).10 years values shown, 100 years values in parenthesis.
Nitrogen oxides (NO_x-N)	0.005 kg	0.00572 kg	NO_X–N = 0.1 * N_2O-N according to Nemecek and Kägi (2007)
Nitrogen (N_2-N) Soil JB3 Soil JB6	 0.15 kg 0.30 kg	 0.172 kg 0.343 kg	Estimated from the SimDen model ratios between N_2O and N_2 by Vinther (2005), see text.
Discharges to soil			
Nitrate leaching Soil JB3 Soil JB6	 1.91 (2.12) kg N 1.50 (1.67) kg N	 2.01 (2.55) kg N 1.52 (2.01) kg N	See text
Phosphate leaching	0.104 kg P	0.1423 kg P	10% of the P applied has the possibility to leach, see text.
Copper (Cu)	0.0276 kg	0.0321 kg	See table I.6
Zinc (Zn)	0.0824 kg	0.1020 kg	See table I.6

Process I.23 to I.25: Fate of the ash from the Samson Bimatech Energy Plant



I.23 Outdoor storage of the ash

This process is identical to process D.11 from Annex D, see this.

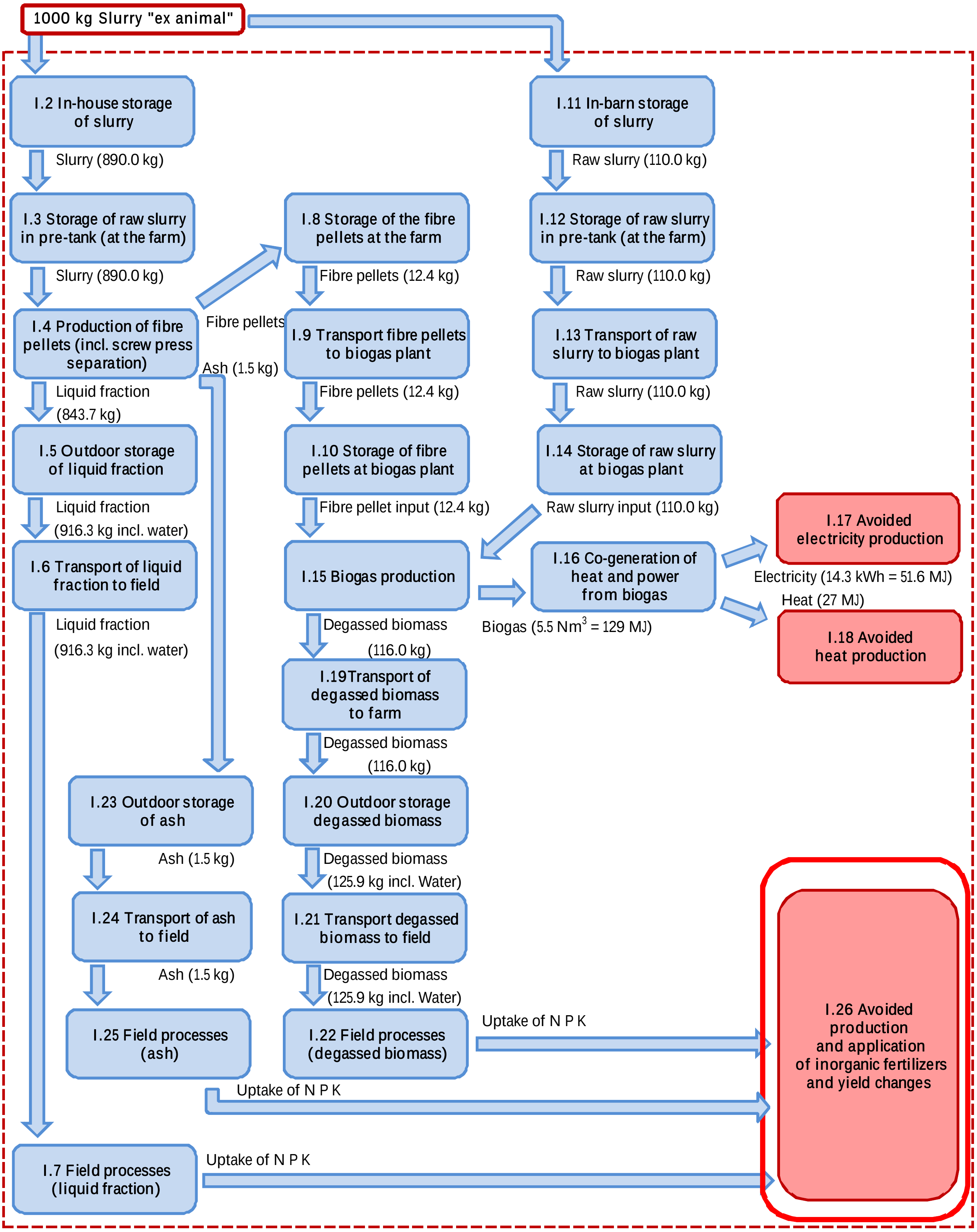
I.24 Transport of ash to field

This process is identical to process D.12 from Annex D, see this.

I.25 Field processes (ash)

This process is identical to process D.13 from Annex D, see this.

Process I.26: Avoided production and application of mineral fertilizers and yield changes



I.26 Avoided production and application of mineral fertilizers

I.26.1 Calculation of the replaced amount of mineral fertiliser

This is calculated using the same method as in Annex F – however, at it involves incineration/ combustion of some of the fibre pellets, the replacement value for this part is accounted as 85% as in Annex D, see section D.8. This is in accordance with a special rule that only applies when slurry is separated and the fibre fraction is combusted. In that case, the fertiliser replacement value should be calculated as 85% of the liquid fraction (Gødskningsbekendtgørelsen (2008), paragraph 21[13])

Table I.8.
Replaced amount of mineral N fertiliser in Annex I. All calculations per 1000 kg slurry ex-animal

Calculations
Step 1: Substitution value for fibre fraction to biogas plant Amount of fibre pellets: 12.388 kg (see figure I.1) N in fibre fraction: 11.75 kg N per 1000 kg fibre fraction (see table I.1 in Annex I) Substitution value: 50% of 11.75 kg per 1000 kg fibre fraction * 12.388 kg fibre fraction / 1000 kg = 0.07278 kg N per 1000 kg slurry ex-animal. This is the substitution value that “belongs” to the fibre fraction that is sent to the biogas plant. This is “input” to the biogas plant.
Step 2: Acknowledging the above, make the weighted sum of the substitution values (liquid and fibre). For raw pig slurry, the substitution value is 75 %. Here rule (a) applies: “The sum of the “mineral fertiliser replacement value” of the outgoing fractions shall be the same as the “mineral fertiliser replacement value” of the ingoing slurry before separation”. The mineral fertiliser replacement value of untreated, raw pig slurry is calculated based on the Danish Norm Data (DJF, 2008), which was also done in Annex A (section A.6.1). From the Danish Norm Data tables, the farmer knows the value of 5.00 kg N per kg slurry ex storage (see also table A.5 and A.1). See further explanation in Annex F, section F.28. For the system, the mineral fertiliser substitution value is then: 5.00 kg N per 1000 kg slurry ex storage * 1086 kg slurry ex storage / 1000 kg slurry ex animal * 75% = 4.0725 kg N per 1000 kg slurry ex-animal. However, only 890.002 kg slurry is being separated. Furthermore, this is a bit more complicated than in Annex H, as 40% of the fibre pellets are combusted internally in the Energy Plant in order to provide heat for the drying of the fibre pellets, see section E.4 in Annex E. It means that when 12.388 kg fibre pellets are sent to the biogas plant (in Step 1 above), actually 12.388 kg * 100/60 = 20.65 kg fibre was produced from the separated fibre fraction. It also means, that 60% of the 890 kg separated slurry should be calculated in accordance with the “separation rules” (as in Annex H), and 40% of the 890 kg should be calculated in accordance with the “combustion rules” (as in Annex E). Calculation for the 60% in accordance with the “separation rules”: The “replacement value” of 60% of the 890 kg slurry BEFORE the separation is: 4.0725 kg N per 1000 kg slurry ex animal * 60% * 890 kg/1000 kg = 2.174715 kg N per 1000 kg slurry ex animal. From this, the replacement value from the fibre fraction in step 1 is subtracted: 2.174715 kg N - 0.07278 kg N = 2.101935 kg N. This is the “replacement value” for the liquid fraction corresponding to the amount of fibre pellets sent to the biogas plant. Calculation for the 40% in accordance with the “combustion rules”: The “replacement value” for the 40% of the 890 kg slurry is calculated as 85% of the N in the liquid fraction. It is calculated in relation to the “ex storage” values. The “ex storage” N for the liquid fraction is 4.712 kg N per

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[13] Gødskningsbekendtgørelsen (2008), paragraph 21: ”Ved beregning af forbruget af kvælstof i husdyrgødning skal følgende andele af det totale indhold af kvælstof i gødningen anvendes: 9) væskefraktion efter forarbejdning hvor fiberfraktionen afbrændes: 85%.”

1000 kg liquid fraction ex storage (see table H.4 in Annex H). It is assumed that this value is ***measured*** on samples of the “ex storage” liquid fraction in correspondence with the Norm Data discussion in Annex F regarding “ex separation” or “ex storage” data. Accordingly, it is assumed that the farmer actually measures 4.712 kg N per 1000 kg liquid fraction ex storage at this point.
The amount of liquid fraction ex storage is 916.301 kg. Accordingly, the “replacement value” for this is:
85% of 4.712 kg N per 1000 kg liquid fraction ex storage * (40% of 916.301 kg / 1000 kg) = 1.4680 kg N

The total “replacement value” for the liquid fraction is then:
2.101935 kg N + 1.4680 kg N = 3.56994 kg N

Mineral fertiliser replacement value for the liquid fraction (at the farm): **3.56994 kg N**

Step 3: Make a weighed sum of the substitution values for the materials entering the biogas plant.
Rule (b): “Mass balance in and out of Biogas Plant – i.e. the “mineral fertiliser replacement value” of the outgoing biomass is calculated in accordance with the ingoing biomass”.

- The raw slurry going directly to biogas plant (without separation) has a mineral fertiliser replacement value of 4.0725 kg N per 1000 kg slurry (as described under step 2 above – 75% of 5.00 kg N ex storage). The amount of this raw slurry is 110 kg (see figure I.1. Its mineral fertiliser replacement value is: 4.0725 kg N per 1000 kg slurry * 110 kg slurry/1000 kg = 0.447975 kg N per 1000 kg slurry ex-animal. This is the substitution value for the raw slurry into the biogas plant.
- At the plant, a biomass mixture is made from this raw slurry and the fibre fraction from step 1, so the substitution value for this input mixture is: 0.07278 kg N (fibre fraction, step 1) + 0.447975 kg N (raw slurry, see above) = 0.520755 kg N.

This is the substitution value for the input biomass mixture going into the biogas plant, and accordingly also the substitution value for the degassed biomass mixture coming out of the biogas plant – i.e. the degassed biomass before separation. This is the substitution value for the end product before separation, used for the further calculations.

Mineral fertiliser replacement value for the degassed biomass: **0.520755 kg N**

Total amount of substituted mineral N fertiliser in the system
3.56994 kg N + 0.520755 kg N = **4.0907 kg N**

I.26.2 Yield changes

Using the same methods as in section F.28.3[14], the overall N difference between Scenario A and Scenario I is (in kg mineral N equivalent):

0.2307 kg N per 1000 kg slurry ex-animal for soil JB3;
0.2368 kg N per 1000 kg slurry ex-animal for soil JB6.

Accordingly, the extra corresponding wheat is:

For soil JB3: 0.2307 kg N surplus * 9.0 kg extra wheat/kg N surplus = 2.08 kg extra wheat (per 1000 kg slurry ex-animal).

For soil JB6: 0.2368 kg N surplus * 8.1 kg extra wheat/kg N surplus = 1.92 kg extra wheat (per 1000 kg slurry ex-animal).

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[14] The values needed to apply the methodology presented in Annex F can be found in the sections for N leaching, namely I.7 (referring to H.7.6) and I.22.7.

I.26.3 Avoided P and K mineral fertilisers

As the amount of P and K in the slurry is the same as in Annex A, as there are no loss of P and K in the system, and as it is assumed that all the slurry fractions (the liquid fraction at the farm, the ash from the combusted fibre pellets and the degassed biomass) ends in the same area, the amount of replaced mineral fertilisers are the same as in Annex A, see section A.6.