

Life Cycle Assessment of Slurry Management Technologies

Marianne Wesnæs og Henrik Wenzel

University of Southern Denmark

Bjørn Molt Petersen

Department of Agroecology and Environment,
Faculty of Agricultural Sciences,
Aarhus University

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Preface

This is the background report from the project “Life Cycle Assessment of Slurry Management Technologies” commissioned by the Environmental Protection Agency of Denmark. The project has been carried out by Marianne Wesnæs and Henrik Wenzel from University of Southern Denmark in cooperation with Bjørn Molt Petersen, Department of Agroecology and Environment, Faculty of Agricultural Sciences, Aarhus University.

The project was carried out in the period of June 2008 - June 2009.

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

- Frank Rosager, Xergi A/S
- Anders Peter Jensen, Xergi A/S
- Jørgen Mertz, Samson-Bimatech A/S
- Gunnar Hald Mikkelsen, Samson-Agro A/S
- Jesper Ravn Lorenzen, Grundfos New Business A/S
- Thorbjørn Machholm, Grundfos Management A/S
- Nils Thorup, Grundfos Management A/S
- Michael Støckler, Agro Business Park
- Jesper Kløverpris, Novozymes
- Randi Lundshøj Dalgaard, LandboMidtØst
- Søren O Petersen, Department of Agroecology and Environment, Faculty of Agricultural Sciences, Aarhus University.
- Sven Sommer, University of Southern Denmark

Furthermore, we would like to acknowledge the contributions from:

- Hanne Damgaard Poulsen, Forskningscenter Foulum
- Thorkild Birkmose, Dansk Landbrugsrådgivning, Landscentret
- Poul Pedersen, Danske Svineproducenter
- Victoria Blanes-Vidal, University of Southern Denmark
- John Hermansen, Institut for Jordbrugsproduktion og Miljø, Forskningscenter Foulum
- Thu Lan Thi Nguyen, Institut for Jordbrugsproduktion og Miljø, Forskningscenter Foulum
- Jens Petersen, Faculty of Agricultural Sciences, Aarhus University.
- Lorie Hamelin, University of Southern Denmark

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.

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 manure by mass (Sommer et al., 2008). *In Danish: Tørstof (TS).*

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.

TAN - Total Available Nitrogen: TAN is the sum of $\text{NH}_3\text{-N} + \text{NH}_4^+\text{-N}$. 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 (for example “ NH_4^+ ” in the heading of a table or in the text combined with “TAN” in the table and vice versa). 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 is the fraction of DM that volatilize when heating the DM at 550°C for one hour. Typically, 80% of DM is VS. 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 ($\text{VS} = \text{DM} - \text{ash}$). *In Danish: Askefrit tørstof eller glødetab.*

VS – easily and heavily degradable. The share of easily degradable VS and heavy degradable VS for pig slurry is based on Sommer et al. (2001, Appendix 5). According to this, the VS in slurry can be divided into an easily degradable fraction and a heavily degradable fraction. The easily degradable fraction is defined as the organic material that is converted to biogas (CO_2 and CH_4) during 14 days in a thermophile reactor and 3 weeks in a mesophile reactor. The content will depend on the pre-treatment of the slurry. The part of VS in slurry that is not degradable in a biogas plant is defined as heavily degradable (1-VS easily degradable).

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 (excretion) and before undergoing any further transformation (i.e. losses or addition). See figure 3.2.

Slurry “ex housing”: Slurry leaving the slurry pits in the housing system. See figure 3.2.

Slurry “ex storage”: Slurry after a long time of outdoor storage. See figure 3.2.

Sammenfatning og konklusioner

Formål

Formålet med dette projekt har været at etablere et fundament der muliggør gennemførelsen af livscyklusvurderinger (LCA) af gyllebehandlingsteknologier i Danmark.

Fundamentet består af:

- En database, der indeholder livscyklusdata for udvalgte gyllebehandlingsteknologier.
- En referencemodel for konventionel gyllebehandling, som er udvidet med modeller for alternative teknologier med data fra de deltagende virksomheder. Modellen er indarbejdet i databasen.
- Nærværende rapport, der indeholder eksempler og resultater af livscyklusvurderinger af udvalgte gyllebehandlingsteknologier.

LCA-fundamentet kan bruges af de deltagende virksomheder til at vurdere den miljømæssige bæredygtighed af en specifik teknologi ud fra et helhedsorienteret livscyklusperspektiv. Formålet med projektet er at kunne svare på spørgsmålet: "Hvad er de miljømæssige fordele og ulemper ved at introducere denne gyllebehandlingsteknologi?" for hver af de nye teknologier.

Fra et samfundsmæssigt perspektiv kan resultaterne bidrage til en afklaring af, hvilke gyllebehandlingsteknologier (eller kombinationer af teknologier), der har det største potentiale for at reducere de inkluderede miljøeffekter.

Referencesystemer og alternative teknologier

I denne rapport er referencesystemerne:

- Gylle fra *slagtesvin*. Gyllen lagres i gyllekanalerne i stalden og udendørs i en betontank (dækket med naturligt flydelag), hvorefter gyllen transporteres og udbringes på marken.
- Gylle fra *malkekvæg*. Gyllen lagres i gyllekanalerne i stalden og udendørs i en betontank (dækket med naturligt flydelag), hvorefter gyllen transporteres og udbringes på marken.

En detaljeret beskrivelse af referencesystemerne findes i kapitel 3.

Referencesystemerne tjener som udgangspunkt for livscyklusvurderingen af de nye gyllehåndteringsteknologier, idet de miljømæssige konsekvenser af at indføre de nye teknologier bliver sammenlignet med referencesystemerne.

De nye gyllebehandlingsteknologier, der er inkluderet i denne rapport, er:

- Forsuring af gylle i et Infarm NH₄⁺ anlæg og efterfølgende lagring og udbringning af den forsurede gylle til mark.

- Mekanisk separering af gylle med et Samson Bimatech separeringsanlæg til en tynd fraktion og en fiberfraktion:
 - Ud fra fiberfraktionen produceres fiberpiller i et Samson Bimatech Energianlæg (som har separeringsanlægget som en integreret del). Fiberpillerne anvendes til:
 - Produktion af varme i Energianlægget
 - Som gødning på marken
 - Den tynde fraktion lagres på samme måde som ubehandlet gylle og spredes derefter på marken.

For at forstå systemerne og forudsætningerne for systemerne er det nødvendigt at læse anekserne i denne rapport.

Der findes mange varierende alternative gyllebehandlingsteknologier i dag. Det har ikke været muligt at inkludere alle disse variationer inden for rammerne af projektet. For eksempel har det ikke været muligt at inkludere en analyse af de miljømæssige konsekvenser af forskellige staldsystemer eller forskellige teknologier til spredning af gylle på marken. Udeladelsen skal ikke tages som udtryk for at disse teknologier ikke er vigtige – nogle af de udeladte teknologier har sandsynligvis meget stor betydning for de samlede miljøbelastninger fra systemerne – de er blot udeladt på grund af projektets tidsmæssige og økonomiske rammer.

Biogas vil blive inkluderet i et efterfølgende projekt.

Basis for sammenligningen: Den funktionelle enhed

De nye gyllehåndteringsteknologier er sammenlignet med referencesystemet med udgangspunkt i "den funktionelle enhed", hvilket betyder, at de alle starter med den samme mængde gylle med den samme sammensætning. Dette er nødvendigt for at gøre scenarierne sammenlignelige med referencesystemet.

Den funktionelle enhed er i denne rapport defineret som: "Håndtering af 1000 kg gylle af dyr."

Sammensætningen af referencegyllen er specificeret i tabellen nedenfor:

Sammensætning af gylle fra slagtesvin og malkekvæg i referencesystemet.
Per 1000 kg gylle "ab dyr", "ab stald" og "ab lager".

	Gylle fra slagtesvin			Gylle fra malkekvæg		
	1000 kg gylle ab dyr	1000 kg gylle ab stald	1000 kg gylle ab lager	1000 kg gylle ab dyr	1000 kg gylle ab stald	1000 kg gylle ab lager
Tørstof (TS)	77.4 kg	69.7 kg	61 kg	125.7 kg	113.2 kg	103 kg
Askeindhold	13.2 kg	13.2 kg	12.2 kg	21.5 kg	21.5 kg	20.6 kg
Omsættelige organiske forbindelser ("volatile solids", VS) Ud af total VS:	64.2 kg	56.5 kg	48.8 kg	104.2 kg	91.7 kg	82.4 kg
- let omsættelig fraktion	41.7 kg	34.0 kg	28.1 kg	50.0 kg	37.5 kg	30.5 kg
- tungt omsættelig fraktion	22.5 kg	22.5 kg	20.7 kg	54.2 kg	54.2 kg	51.9 kg
<i>Total-N (DJF, 2008)</i>	<i>6.60 kg</i>	<i>5.54 kg</i>	<i>5.00 kg</i>	<i>6.87 kg</i>	<i>6.41 kg</i>	<i>6.02 kg</i>
Total-N i denne rapport	6.60 kg	5.48 kg	4.80 kg	6.87 kg	6.34 kg	5.79 kg
NH ₄ ⁺ -N	No data	No data	3.60 kg	No data	No data	3.47 kg
Total-P	1.13 kg	1.13 kg	1.04 kg	1.02 kg	1.03 kg	0.98 kg
Kalium (K)	2.85 kg	2.85 kg	2.60 kg	5.81 kg	5.90 kg	5.65 kg
Kulstof (C)	37.0 kg	33.3 kg	29.2 kg	55.2 kg	49.7 kg	45.2 kg
Kobber (Cu)	30.0 g	30.0 g	27.6 g	12.1 kg	12.1 kg	11.6 g
Zink (Zn)	89.4 g	89.4 g	82.4 g	23.4 kg	23.4 kg	22.4 g
Massefylde	1053 kg per m ³					
pH	7.8	7.8	7.8	7.8	7.8	7.8

Systemgrænser

I princippet bør alle miljøpåvirkninger fra alle berørte processer i hele livsforløbet medtages, når man gennemfører en livscyklusvurdering. Når man sammenligner alternative systemer, er det dog ikke nødvendigt at inkludere processer, der er identiske i de sammenlignede systemer.

I denne rapport er der fokuseret på forskellene mellem systemerne, og de processer, der er identiske for referencesystemet og de undersøgte alternative teknologier, er udeladt. Fælles for alle systemerne er processerne forud for dyrenes udskillelse af gyllen, dvs. produktion af svin og kvæg, fremstilling af foder, medicin, hormoner, staldbygninger osv. Endvidere er energiforbruget i stalden de samme i de undersøgte systemer og er derfor udeladt. Desuden er emissioner af metan (CH₄) fra kvæg udeladt. Emissionerne af metan er udeladt, fordi de er identiske i de inkluderede systemer, men også fordi de ikke er relevante for formålet med projektet ("Hvad er de miljømæssige fordele og ulemper ved at introducere denne teknologi for gyllebehandling?"). Udgangspunktet er den gylle, der udskilles fra dyrene i stalden. Systemet starter med andre ord, når gyllen forlader dyret og rammer gulvet i stalden.

Udeladt er således emissioner af CH₄ og CO₂ fra dyrene.

Inkluderet er til gengæld emissioner fra gyllen på og under staldgulvet og emissionerne fra alle de følgende processer; opbevaring af gyllen i stalden, pumpning, udendørs lagring, transport og når gyllen spredes på marken. Endvidere er den mineralske gødning (N, P og K gødning), som gyllen fortrænger pga. indholdet af næringsstoffer inkluderet. Inkluderet er også inkorporeringen af kulstof i jorden.

I princippet er afgrøderne ikke inkluderet i systemet. Det har dog været nødvendigt at inkludere mindre mængder "øget udbytte", da nogle af gyllehåndteringsteknologierne medfører et øget høstudbytte. Dette er uddybet i rapporten. Endvidere er der for hvert af referencesystemerne for slagtesvin og malkekvæg defineret en typisk afgrøderotation, da emissionerne fra marken afhænger af afgrøden.

Energiforbrug til gyllehåndteringsteknologierne er inkluderet, for eksempel energi til pumpning og omrøring af gyllen samt til transport. Energiforbrug i stalden er ikke inkluderet, men det ekstra energiforbrug til teknologierne er inkluderet, f.eks. energiforbrug til forsøringsanlægget samt til fremstilling af svovlsyren i forsøringsscenariet.

I nogle livscyklusvurderinger inkluderes biogent kuldioxid (CO_2) ikke, da det betragtes som "neutralt" (afgrøder optager CO_2 når de vokser, og hvis afgrøden bliver brændt, ender CO_2 tilbage i atmosfæren). I denne livscyklusvurdering er biogent CO_2 inkluderet. For det første bidrager et biogent CO_2 -molekyle præcist lige så meget til global opvarmning som et fossilt CO_2 -molekyle. For det andet er det meget vigtigt for resultaterne af denne livscyklusvurdering at identificere, hvor stor en andel af det kulstof, der tildeles til jorden, som indbygges i jorden og hvilken andel, der emitteres som CO_2 . Fordi emissionerne af biogent CO_2 er forskellige for de forskellige teknologier, er det vigtigt at inkludere den biogene CO_2 og den globale opvarmning som følge af det. På denne måde inkluderes forskellen mellem det biogene CO_2 og den mængde kulstof, der indbygges i jorden i sammenligningen mellem referencesystemet og scenarierne for de nye gyllehåndteringsteknologier.

Det bør understreges, at livscyklusmetoden er en simplificeret model af miljøpåvirkningerne. Mange af processerne i gyllehåndtering er komplekse og afhænger af mange variable. Dette gælder specielt processerne på marken. Som den simple model, livscyklusvurderinger er, er det ikke muligt at håndtere dynamisk modellering. I LCA omsættes de dynamiske data til et sæt af diskrete parametre og værdier, som udvælges omhyggeligt således, at de på bedst mulig måde repræsenterer situationen. Dette er gjort i kapitel 3. De diskrete værdier kan ændres i følsomhedsanalyser, men ikke "dynamisk".

Tidsmæssig, geografisk og teknologisk dækning

For referencesystemet har det været hensigten at opstille et "typisk dansk scenarie", baseret på gennemsnitlig teknologi. Scenariet skal repræsentere "tilstanden i 2008". For de nye alternative teknologier er det hensigten at anvende BAT (Best available technology), da disse teknologier repræsenterer fremtidig teknologi. Da denne rapport dækker gyllehåndtering under danske forhold (staldsystemer, lagerfaciliteter, jordtyper, gyllespredningsteknologier og elektricitetsproduktion) er det ikke muligt at overføre resultaterne direkte til andre europæiske lande uden justering.

Miljøpåvirkninger og ressourcer

De kategorier af miljøpåvirkninger og ressourcer, der er udvalgt i denne rapport, er primært baseret på den danske UMIP-metode, kombineret med den europæiske LCA-metode "Impact 2002+":

- Global opvarming (UMIP)
- Forsuring (UMIP)
- Nærings saltsbelastning for N og P (UMIP)
- Fotokemisk ozondannelse ("smog") (UMIP)
- Uorganiske partikler, der påvirker åndedrættet ("Respiratory inorganics" fra Impact 2002+)
- Fosfor som ressource
- Ikke-fornyelige energiressourcer (Impact 2002+)

Referencesystemet

Beskrivelse af referencesystemet

Referencesystemet i denne rapport repræsenterer ikke et gennemsnit af gyllehåndteringen i Danmark, men skal i højere grad være repræsentativt for "typiske" systemer i Danmark. Der er derfor forsøgt at identificere de metoder, der er mest udbredte og anvendt i dag. Referencesystemet dækker ikke alle situationer og muligheder.

Der er to referencesystemer: Et for gylle fra *slagtesvin* og et for gylle fra *malkekvæg*. De væsentligste antagelser og forudsætninger er beskrevet i det følgende:

- Referencescenariet for slagtesvin er baseret på et staldsystem med fuldspaltegulv, mens det for malkekvæg er baseret på et staldsystem med sengestald og spaltegulv.
- Gyllen pumpes fra fortanken til en udendørs lagertank af beton. Det er forudsat at gyllen er dækket af et flydelag (snittet halm for gylle fra slagtesvin og naturligt flydelag for gylle fra malkekvæg).
- Transportafstanden fra lager til mark er antaget at være 10 km.
- Gyllen spredes på marken med slangeudlægger.
- Der er udvalgt to jordbundtyper til at repræsentere danske forhold. Jordtype JB3 er valgt til at repræsentere sandholdig jord, mens jordtype JB6 repræsenterer lerholdig jord (for definitioner af disse, se afsnit 3.1).
- Det antages, at gyllen tildeles til afgrøder (modelleret med 6 års rotation). Relevante afgrødetyper er defineret for henholdsvis gylle fra slagtesvin og gylle fra malkekvæg. Som nævnt ovenfor, er afgrøderne ikke inkluderet indenfor systemets afgrænsning. Afgrøderne er udelukkende defineret, da optagelsen af næringsstoffer og flere emissioner afhænger af afgrøden, og for at kunne modellere den videre skæbne for den del af N, der ikke fjernes med afgrøden.

Data for referencesystemet

Data for referencesystemet er i høj grad baseret på to hovedreferencer: Det danske Normsystem for kvælstof, fosfor og kalium i husdyrgødning (Poulsen et al. (2001), DJF (2008a) and DJF (2008b)) samt IPCC (2006). Disse data bør betragtes som temmelig "statiske og brede estimater". Disse referencer er valgt både fordi anvendelsen af dem er vidt udbredt (Normsystemet danner blandt andet grundlag for Plantedirektoratets årlige vejledning om gødsknings og harmoniregler (Plantedirektoratet, 2008b) samt anvendes til årlige opgørelser af nationale statistikker for drivhusgasemissioner, se Nielsen et al., 2008a og Nielsen et al., 2008b). Endvidere har det ikke været muligt at inkludere anvendelsen af avanceret modellering af emissionerne inden for projektets rammer. Det har imidlertid ikke været uproblematisk at bruge data fra det danske Normsystem sammen med data fra IPCC (2006), først og fremmest fordi de to referencer ikke er afstemt med hinanden med hensyn til massebalancer og emissioner. Endvidere er opholdstid i stald og lager ikke defineret, og emissioner fra fortanken fremgår ikke specifikt.

Resultater

Det skal understreges, at væsentlige forudsætninger og data i denne rapport er udvalgt til at repræsentere danske forhold. Resultaterne kan ikke umiddelbart overføres til andre lande på grund af forskelle i staldsystemer, opholdstid i stald og lager, udbringningsmetoder af gyllen, forskelle mht. temperatur og klima, jordtyper samt mange andre faktorer.

Konklusionerne i denne rapport gælder kun under de forudsætninger, der er beskrevet i rapporten. For eksempel vil andre udbringningsmetoder, utildækket lagring af gyllen i lagertanken og forskelle i gyllens sammensætning ændre resultaterne betydeligt.

Tilsyneladende har hidtidig dansk forskning på gylle-området i høj grad fokuseret på NH_3 -emissioner, mens der mangler forskning inden for drivhusgas-emissioner. På trods af usikkerhederne kan det konkluderes, at de væsentligste bidrag til den globale opvarmning fra gylle kommer fra emissioner af metan (CH_4) fra stald og lager samt fra lattergasemissioner (N_2O) samt CO_2 fra marken. Bestræbelser på at reducere disse er derfor vigtige.

Bidrag til miljøeffekten "forsuring" er domineret af NH_3 -emissioner fra stald og fra lager samt fra mark efter udbringning.

Næringssaltbelastning med nitrogen (N) er domineret af udvaskning af N fra mark. Endvidere bidrager NH_3 -emissionerne fra stald, lager og mark i nogen grad.

Resultaterne for næringssaltsbelastning af fosfor (P) er præget af mangel på data af tilstrækkelig kvalitet, og resultaterne bør derfor tolkes med forsigtighed. Det er uden for rammerne af nærværende projekt at foretage en sammenligning af hvorvidt udvaskningen af fosfor er højest fra gylle eller fra mineralsk fosforgødning. Det kan således *ikke* konkluderes at der er en "netto reduktion" af fosforudvaskning fra systemet selv om den mineralske fosforgødning trækkes fra.

De største bidrag til miljøeffekten "Fotokemisk Ozondannelse" kommer fra CH_4 emissioner fra stald og lager.

Bidragene til miljøeffekten "Uorganiske partiklers indvirkning på menneskers åndedræt" ("Respiratory inorganics") domineres i referencesystemet fuldstændigt af NH_3 -emissioner.

El-forbruget til pumper og omrøring af gyllen er væsentligt for forbruget af ikke-fornyelige energiressourcer. Til gengæld er elforbruget er temmelig ubetydeligt for alle de øvrige miljøeffekter og kategorier.

Transport bidrager også til forbruget af ikke-fornyelige energiressourcer. Endvidere bidrager transport en lille andel til miljøeffekterne "Fotokemisk ozondannelse" samt "Uorganiske partiklers indvirkning på menneskers åndedræt" (forårsaget af små partikler, der udledes under kørslen). Transport er helt ubetydelig for resten af effektkategorierne.

Forskellen mellem jordtype JB3 (sandholdig jord) og JB6 (lerholdig jord) er kun værd at bemærke for akvatisk eutrofiering (N) (nitratudvaskning), hvor udvaskningen er ca. 15-20% lavere for lerholdig jord i forhold til sandholdig jord.

Scenarie for forsurening af gylle i et Infarm NH_4^+ forsøringsanlæg

Formål

En sammenlignende livscyklusvurdering er gennemført for at besvare spørgsmålet: "Hvad er de miljømæssige fordele og ulemper ved forsurening af gylle i et Infarm NH_4^+ anlæg i forhold til referencesystemet?". Dette gøres ved at sammenligne miljøpåvirkningerne fra et "Infarm NH_4^+ forsørings-scenarie" med miljøpåvirkningerne fra referencesystemet.

De miljømæssige konsekvenser og konklusioner i dette kapitel bygger i vid udstrækning på data og oplysninger, der er leveret af Infarm, samt på data lavet for Infarm i andre sammenhænge. Konklusionerne er baseret på disse oplysninger, og forfatterne har ikke haft mulighed for at eftervise data.

Beskrivelse af systemet

I Infarm NH_4^+ forsøringsanlægget forsures gylle fra svin eller kvæg ved tilsætning af svovlsyre (H_2SO_4). Svovlsyren reducerer pH og den kemiske balance mellem ammonium (NH_4^+) og ammoniak (NH_3) ændres, hvilket betyder, at det primært forefindes i form af ammonium (NH_4^+). Da det kun er ammoniak (NH_3) der fordampes, er pH-værdien af gyllen en afgørende faktor for, hvor meget NH_3 der fordampes i stald, lager og på marken. Forsuring af gyllen har desuden betydning for andre faktorer. For eksempel kan brugen af svovlsyre være en fordel, da det tilføjer svovl til marken (hvilket kan have en gødningsvirkning).

Resultater

Resultaterne af den sammenlignende livscyklusvurdering viser at:

- Forsuring af gylle reducerer NH_3 emissioner betydeligt. Da NH_3 giver de største bidrag til miljøpåvirkningerne "Forsuring" og "Uorganiske partiklers indvirkning på menneskers åndedræt" ("Respiratory inorganics"), er det samlede bidrag til disse er reduceret betydeligt, når man sammenholder forsuringsscenariet med referencesystemet. Bidraget til "forsuring" er reduceret med 40-90% i forhold til bidragene fra referencesystemet for svinegylle og 30-66% i forhold til bidragene fra referencesystemet for gyllen fra malkekvæg. Bidraget til "Respiratory inorganics" er reduceret med 30-90% i forhold til bidragene fra referencesystemet for svinegylle og 20-70% i forhold til bidragene fra referencesystemet for gyllen fra malkekvæg.
- Forsuring af gylle reducerer CH_4 emissionerne, sandsynligvis på grund af, at den biologiske aktivitet hæmmes ved lav pH. Dette fører til en reduktion af bidragene til miljøpåvirkningerne "Global opvarmning" og "Fotokemisk ozondannelse". Bidraget til global opvarmning er reduceret med 10-36% i forhold til bidragene fra gyllen i referencesystemerne for svin og malkekvæg.
- Da forsuret gylle indeholder mere N "ab lager" end den ubehandlede gylle (på grund af de reducerede NH_3 -emissioner), er bidraget til nitratudvaskning højere for forsuret gylle. Dette modsvarer dog i nogen grad af at systemet har et "fradrag": Da landbrugsjorden tilføres mere N med den forsurede gylle, øges udbyttet af afgrøde. Denne ekstra mængde afgrøde trækkes fra, hvorved forsuringsscenariet opnår et fradrag (en godskrivning). Dette er gjort for at ligestille "forsuringsscenariet" med referencesystemet - ved sammenligning af systemer i livscyklusvurderinger er det meget vigtigt, at systemerne har samme mængde "output" (ellers er de ikke sammenlignelige). Når man medregner fradraget og inddrager de usikkerheder, der er på dette fradrag, er der ingen signifikant forskel på bidraget fra forsuringsscenariet og referencesystemet set i et 10-årigt perspektiv. Med et perspektiv på 100 år vil forsuringsscenariet øge bidraget til nitratudvaskning med 10-30%, når man sammenligner med bidraget fra gyllen i referencesystemet.
- Forsuring af gylle påvirker ikke udvaskning af fosfor, da der er samme mængde fosfor i forsuringsscenariet som i referencesystemet.
- Forbruget af ikke-fornyelige energiresourcer ikke er væsentlig højere for forsuringsscenariet end for referencesystemet, da det ekstra forbrug på grund af elforbruget opvejes af fradraget for det højere landbrugsudbytte, som forklaret ovenfor.
- Forskellen mellem jordtype JB3 og JB6 kun bemærkelsesværdig for akvatisk eutrofiering (N) (nitratudvaskning). Forskellen er ikke af betydning for de overordnede konklusioner.

Scenarie for Samson Bimatech Energianlæg

Formål

En sammenlignende livscyklusvurdering er gennemført for at besvare spørgsmålet: "Hvad er de miljømæssige fordele og ulemper ved at bruge svinegylle til fremstilling og afbrænding af fiberpiller i et Samson Bimatech Energianlæg (med produktion af varme) i forhold til referencesystemet?".

De miljømæssige konsekvenser og konklusioner i dette kapitel bygger i vid udstrækning på data og oplysninger, der er leveret af Samson Bimatech, samt på data lavet for Samson Bimatech i andre sammenhænge. Konklusionerne er baseret på disse oplysninger, og forfatterne har ikke haft mulighed for at eftervise data.

Beskrivelse af systemet

Fiberpillerne fremstilles i en række trin, der omfatter separering af gylle, tørring af fiberfraktionen og fremstilling af fiberpiller. Fiberpillerne kan bruges til varmeproduktion på bedriften i et Samson Bimatech Energianlæg. Tørringen af våde fibre kræver varme og dette forbruger ca. 40% af den energi, der produceres ved forbrænding af fiberpillerne. Overskudsvarmen fra Energianlægget (i.e. ca. 60% af den producerede varme) erstatter den varmeproduktion, der ellers skulle have været anvendt til opvarmning af stuehuset på bedriften. Det er antaget, at stuehuset ville have været opvarmet med let fyringsolie (og i følsomhedsanalyserne halm eller træpiller). Den "erstattede varme" trækkes fra systemet.

Vurderingen omfatter kun svinegylle, da målinger for kvæggylle ikke var til rådighed da data blev indsamlet. Data for kvæggylle blev indsamlet lige før afslutning af projektet (maj 2009). Det var imidlertid ikke muligt at indarbejde data for kvæggylle inden for tidsrammerne af projektet.

Resultater

Resultaterne af livscyklusvurderingen viser at:

Det samlede bidrag til den globale opvarmning for scenariet for Samson Bimatechs energianlæg er på samme niveau som bidraget fra referencesystemet (når man tager usikkerheden på data med i betragtning). Forbrænding af fiberpiller fra energianlægget giver CO₂-emissioner, med det bliver delvist opvejet af at der er mindre emissioner af CO₂ fra marken fra den tynde fraktion (fra separationen (i forhold til at anvende ubehandlet gylle på marken) samt på grund af fradraget fra den "erstattede varme" som nævnt ovenfor.

NH₃-emissionerne er reduceret for "Samson Bimatech energianlægs-scenariet" i forhold til referencesystemet som følge af reducerede NH₃-emissioner fra anvendelsen af den tynde fraktion til mark sammenlignet med den ubehandlede gylle i referencesystemet. De reducerede NH₃ emissioner fører til en lille reduktion af de samlede bidrag til miljøeffekten "forsuring".

Bidraget til akvatisk eutrofiering med N (næringssaltsbelastning – "nitratudvaskning") er en smule mindre for "Samson Bimatech energianlægs-scenariet", da der ender en mindre del N på marken, fordi en del af gyllens N er fjernet til produktion af fiberpiller og forbrændt.

Bidraget til akvatisk eutrofiering (næringssaltsbelastning) med fosfor (P) er uændret.

"Samson Bimatech energianlægs-scenariet" har et højere bidrag til miljøpåvirkningen "fotokemisk ozondannelse" på grund af emissioner af nitrogenoxider (NO_x) under forbrændingen af fiberpillerne. Dette er kun delvist opvejet af en mindre reduktion af CH_4 -emissioner fra lagring af den tynde fraktion af den separerede gylle i forhold til lagring af referencegyllen (på grund af et lavere indhold af C i den tynde fraktion). Der er en betydelig usikkerhed på NO_x -emissionerne fra energianlægget hvilket skyldes, at teknologien er en forholdsvis ny teknologi, der stadig er under udvikling, og som ikke er gennemtestet på nuværende tidspunkt.

Bidraget til miljøeffekten "Uorganiske partiklers indvirkning på menneskers åndedræt" ("Respiratory inorganics") er på samme niveau for "Samson Bimatech energianlægs-scenariet" som for referencesystemet (når man tager usikkerheden på data med i betragtning). NO_x fra Energianlægget øger bidraget, men dette opvejes af de reducerede bidrag fra NH_3 fra den tynde fraktion på marken, som beskrevet ovenfor.

Samson Bimatechs Energianlæg gennemgår fortsat produktudvikling, og teknologien skal ses som værende i sin "barndom". På den ene side betyder det, at det har været vanskeligt at opnå høj kvalitet af data for separeringen og for emissioner fra energianlægget, hvilket har stor indflydelse på NO_x -emissionerne. På den anden side betyder det sandsynligvis, at der er gode muligheder for at forbedre teknologien. NO_x -emissionerne vil sandsynligvis kunne reduceres betydeligt ved at anvende NO_x reducerende teknologi i Samson Bimatechs Energianlæg. Separeringen har stor indflydelse på den samlede miljøpåvirkning, da de største bidrag kommer fra den tynde fraktion af den separerede gylle (lager og mark). Den tynde fraktion har så stor betydning fordi den indeholder en relativt stor andel af det samlede N og C i systemet. Resultaterne afhænger derfor i høj grad af den andel N og C, der overføres til fiberfraktionen. For Samson Bimatechs separering overføres 29,6% af tørstof 6,8% af N til fiberfraktionen. Det betyder, at den tynde fraktion indeholder de resterende 70,4% tørstof og 93,2% N. Hvis denne andel reduceres ved produktudvikling af anlægget, vil det reducere den samlede miljøpåvirkning fra systemet.

Scenarie for anvendelse af fiberpiller som gødning

Formål

En sammenlignende livscyklusvurdering er gennemført for at besvare spørgsmålet: "Hvad er de miljømæssige fordele og ulemper ved at bruge svinegylle til fremstilling af fiberpiller i et Samson Bimatech Energianlæg og at anvende fiberpillerne som gødning på marken - i forhold til referencesystemet?".

Beskrivelse af systemet

Scenariet i dette afsnit er meget lig det foregående scenarie for Samson Bimatechs energianlæg. I dette afsnit bliver fiberpillerne blot ikke anvendt til varmeproduktion, men i stedet spredes de på marken som gødning.

Det skal understreges, at dette scenarie mest er udført som en "test af en fremtidig mulighed", da fiberpillerne ikke anvendes som gødning i dag.

Resultater

Når man tager usikkerheden på data med i betragtning, er der ingen signifikant forskel på de samlede bidrag til global opvarmning, akvatisk eutrofiering (P) (næringssaltsbelastning), "Uorganiske partiklers indvirkning på menneskers åndedræt" ("Respiratory inorganics") og forbruget af fosfor som en ressource, når man sammenligner scenariet med "Fiberpiller anvendt som gødning" med referencesystemet.

"Fiberpiller anvendt som gødning"-scenariet giver en smule mindre bidrag til miljøeffekterne "forsuring" og akvatisk eutrofiering (N) end referencesystemet (på grund af reducerede NH_3 -emissioner og reduceret N udvaskning fra den tynde fraktion i forhold til ubehandlet gylle).

Bidraget til "fotokemisk ozondannelse" er lidt højere fra "Fiberpiller anvendt som gødning"-scenariet i forhold til referencesystemet.

Forbruget af ikke-vedvarende energiressourcer er betydeligt højere forårsaget af elforbruget i Samson Bimatechs energianlæg.

Summary and conclusions

Objectives of the study

The objective of this study is to establish a foundation for Life Cycle Assessments of slurry management technologies in Denmark.

The LCA foundation consists of:

- A database containing Life Cycle Data for selected slurry management technologies,
- A reference model for conventional slurry management, which is expanded with models for alternative technologies and data from the contribution of participating companies. The models are part of the database.
- This report, containing examples and results of Life Cycle Assessments performed for selected slurry management technologies.

The LCA foundation can be used by the contributing companies for evaluating the environmental sustainability of a specific technology from a holistic Life Cycle perspective. The goal of the study is to answer the question for each alternative technology: “What are the environmental benefits and disadvantages of introducing this technology for slurry management?”

From a societal perspective the results can contribute to a clarification of which slurry management technologies (or combination of technologies) having the largest potential for reducing the overall environmental impacts.

Reference scenarios and alternatives

In this study, the reference scenarios are:

- Slurry from *fattening pigs*, stored in the slurry pits below the animals in the housing units, stored in a concrete slurry tank (covered by a natural floating layer), transported and applied to field.
- Slurry from *dairy cows*, stored in the slurry pits below the animals in the housing units, stored in a concrete slurry tank (covered by a natural floating layer), transported and applied to field.

A detailed description of the reference scenarios are specified in chapter 3.

The reference scenarios serve as a basis for the assessment of the environmental impacts of the alternative technologies for slurry management. The environmental consequences of choosing alternative technologies are compared to the reference scenarios.

The slurry treatment technologies included in this report are:

- Acidification of slurry and subsequent storage and application of the acidified slurry to field (Infarm NH₄⁺ plant).

- Mechanical separation of slurry into a fibre fraction and a liquid fraction (Samson Bimatech Separation plant):
 - Use of the fibre fraction for fibre pellets production and use of the pellets for:
 - Application to field
 - Heat production in a Samson Bimatech Energy Plant
 - Application of the liquid fraction directly to the field

For a fully understanding of the preconditions and the systems, reading of the Annexes is required.

There is a huge variety of alternative technologies for slurry management. It has not been possible to include all of these various alternatives within the framework of this study. For example, it has not been possible to include the environmental impacts changed management of the slurry in the housing system or the various technologies for application of slurry to the field. The exclusion should *not* be seen as these technologies are regarded as unimportant – some of them most likely have huge significance for the overall environmental impacts – they are only excluded due to the time and budget constraints of the project.

Biogas production will be included in an upcoming report.

Basis for the comparison: The functional unit

The new technologies are compared to the reference system based on the same “functional unit”, which means that they all start with the same amount of pig slurry (or dairy cow slurry) with the same composition. This is necessary in order to make the scenarios comparable.

The functional unit in this study is: “Management of 1000 kg slurry ex animal”.

The composition of the reference slurry is specified in the tables below:

Characteristics of slurry from fattening pigs and from dairy cows in the reference scenario. Per 1000 kg of slurry “ex animal”, “ex housing” and “ex storage”.

	Fattening pig slurry			Dairy cow slurry		
Total mass	1000 kg Slurry ex animal	1000 kg Slurry ex housing	1000 kg Slurry ex storage	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	125.7 kg	113.2 kg	103 kg
Ash content	13.2 kg	13.2 kg	12.2 kg	21.5 kg	21.5 kg	20.6 kg
Volatile solids (VS)	64.2 kg	56.5 kg	48.8 kg	104.2 kg	91.7 kg	82.4 kg
Of total VS:						
- easily degradable	41.7 kg	34.0 kg	28.1 kg	50.0 kg	37.5 kg	30.5 kg
- heavily degradable	22.5 kg	22.5 kg	20.7 kg	54.2 kg	54.2 kg	51.9 kg
<i>Total-N (DJF, 2008)</i>	<i>6.60 kg</i>	<i>5.54 kg</i>	<i>5.00 kg</i>	<i>6.87 kg</i>	<i>6.41 kg</i>	<i>6.02 kg</i>
Total-N in this study	6.60 kg	5.48 kg	4.80 kg	6.87 kg	6.34 kg	5.79 kg
NH ₄ ⁺ -N	No data	No data	3.60 kg	No data	No data	3.47 kg
Total-P	1.13 kg	1.13 kg	1.04 kg	1.02 kg	1.03 kg	0.98 kg
Potassium (K)	2.85 kg	2.85 kg	2.60 kg	5.81 kg	5.90 kg	5.65 kg
Carbon (C)	37.0 kg	33.3 kg	29.2 kg	55.2 kg	49.7 kg	45.2 kg
Copper (Cu)	30.0 g	30.0 g	27.6 g	12.1 kg	12.1 kg	11.6 g
Zinc (Zn)	89.4 g	89.4 g	82.4 g	23.4 kg	23.4 kg	22.4 g
Density	1053 kg per m ³	1053 kg per m ³	1053 kg per m ³	1053 kg per m ³	1053 kg per m ³	1053 kg per m ³
pH	7.8	7.8	7.8	7.8	7.8	7.8

System boundaries

In principle, all environmental impacts from all processes in the entire chain have to be included; however, when comparing alternatives, it is not necessary to include processes that are identical in the compared systems.

In this study, focus has been put on the differences, and the processes, that are identical for the reference scenarios and the alternative technologies have been left out.

Common for all the scenarios in this study are all the processes “up-stream” of the slurry excretion, i.e. production of pigs and cattle, production of feed, medicine, hormones, housing systems etc. Also the energy consumption within the housing system is assumed to be the same, and all common processes are excluded. Furthermore, methane emissions from the cattle in the housing units are *not* included. These are left out as they are identical in all scenarios, but also as they are not relevant for the goal of the study (“What are the environmental benefits and disadvantages of introducing slurry management technology X?”). The starting point is, thus, the slurry excreted in the housing units. In other words, the system starts when the slurry leaves the pig or the cow and hits the floor or the slurry pits in the housing system, see figure 2.2.

Gaseous emissions (methane, carbon dioxide) from the animals are *not* included within the system boundaries (as changed slurry management has no influence on the enteric fermentation and on the respiration).

Included are only the gaseous emissions from the *slurry* and the emissions from all the slurry management that follows; in-house handling, pumping,

storage, transport and application to the field. These are the focus of this report.

Included within the system boundaries for the reference scenario are emissions from the slurry in the housing units and in the pre-tank, outdoor storage, transport, application to field, avoided / reduced production of mineral fertilisers due to the fertiliser value of the slurry and organic matter incorporation in the soil which include carbon sequestration. A flow diagram for the reference scenario is shown in figure 3.1 in chapter 3.

In principle, the crops on the field are not included within the system boundaries. However, it has been necessary to include small amounts of “increased crop production” for some of the new technologies when the slurry management actually leads to an increase of the crop yield. This is elaborated later. In order to specify the emissions from the field, a reference crop rotation for pig farms and cattle farms has been set up in the system description in section 3.1. This has been necessary in order to estimate the input and output from the fields.

The energy consumption for all the slurry management technologies is included, for example the energy consumption for pumping, for the separation processes or for transport. The energy consumption in the housing units is generally not included, however, the *extra* energy consumption for the “add-on” technology in the housing system is included, and for example the consumption of energy / chemicals for acidification of the slurry in the housing units is taken into account.

In some Life Cycle Assessments, biogenic carbon dioxide (CO_2) is not included as it is regarded as “neutral” (Crops take up CO_2 when growing, and when the crop is incinerated, the CO_2 ends back in the environment). In this Life Cycle Assessment biogenic CO_2 is included. First of all, biogenic CO_2 contributes exactly as much to global warming as CO_2 from fossil fuels. Secondly, it is very important for the results of this study to identify how much of the carbon applied to the soil that will be incorporated in the soil and how much that is emitted as CO_2 . As the amount of biogenic CO_2 emissions are different from the various technologies, it is important to include the biogenic CO_2 and the global warming potential caused by it. In this way, the difference between the biogenic CO_2 and the C stored in the soil is included in the comparison between the reference scenario and the scenarios for each of the new technologies.

It should be emphasized that the Life Cycle Assessment methodology is a simplified model of the environmental impacts. A lot of the processes in the slurry management chain are complex and dependent upon many variables, especially the field processes. The simplified Life Cycle Assessment methodology is not capable of handling dynamic modelling. In LCA, these dynamic data are translated into a set of discrete parameters and values that are carefully chosen in order to represent the situation as well as possible (as done in section 3 when defining the reference scenarios), and these parameters can be changed for analysing the uncertainty. However, LCA is not suitable as e.g. a dynamic model for the analysis of the development during the next 10-20 years, showing the results year by year.

Temporal, geographical and technological coverage

The intended technology level for the reference scenario is to set up a “typical Danish scenario”, based on “average technology”. The scenario should represent “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. This study covers slurry management under Danish conditions (cattle housing systems, storage facilities, soil types, application methods, and energy production) and it is not possible to transfer the results directly to other European countries without adjustments.

Environmental Impacts and Resources

The environmental impact categories in this study are primarily based on the Danish EDIP method, supplied with two impacts from the method “Impact 2002+”:

- *Global warming* (climate change) (EDIP).
- *Acidification*, which causes damage to forest, other vegetation and lakes (EDIP).
- *Eutrophication* (nutrient enrichment), which causes damage to lakes and coastal marine waters (EDIP).
- *Photochemical ozone formation (“smog”)*, which is caused by reactive compounds forming ozone on the lower layer of the atmosphere, i.e. at the human breathable level, causing respiratory problems for humans and potentially reducing growth of crops. It is commonly known as “smog” in large cities (EDIP).
- *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 from the media. Impacts from ammonia, nitrogen oxides and sulphur dioxide are included in this category (Impact 2002+).
- *Phosphorus* (as a resource) has been chosen as a separate impact indicator category, as the phosphorus resource issue and recycling of phosphorus is particularly relevant for this project. Phosphorus is an essential element for plant and animal nutrition. In case of depletion there could be a serious problem for the global food production since phosphorus is such an essential ingredient in fertilisers, especially because there are no substitutes.
- *Resources*. The consumption of non-renewable energy resources is included as this is an indicator of the energy consumption of the system (Impact 2002+)

Reference scenarios

System description for the reference scenarios

The reference scenarios in this report do not represent an average of the slurry management systems in Denmark, but should rather be seen as a representative of “typical” systems. Accordingly, an attempt to identify the most commonly used methods has been made. The reference scenarios do not cover all situations and possibilities.

There are two reference scenarios: one for *fattening pigs* and one for dairy cows. In short, the main preconditions for the reference scenario are:

- The reference scenario for fattening pigs is based on a housing system with “*Fully slatted floor*” for fattening pigs and “*cubicle housing system with slatted floor* (1.2 m channel)” for dairy cows.
- From the pre-tank in connection with the housing units the slurry is pumped to the outdoor storage in concrete slurry tanks and *covered by a floating layer*.
- The *transport distance* from storage to application to fields has been estimated to 10 km.
- The slurry is applied with *trail hose tankers to the field* in the reference scenarios.
- Relevant *soil types* in Denmark are clay soil and sandy soil. In the modelling, soil type JB3 has been used representing sandy soil and soil type JB6 has been used representing clayey soil ¹.
- It is assumed that the slurry is applied to all crops in the crop rotation pattern (six year rotation). Crop types relevant for respectively pig slurry and dairy cow slurry are specified. As mentioned above, 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.

Data for the reference scenario

Data for the reference scenario is to a high degree based on two main references: Data from the Danish Normative system for assessing manure composition (Poulsen et al. (2001), DJF (2008a) and DJF (2008b)) and IPCC (2006). These data should be regarded as rather “static and rough estimates”. These data have been used as these are widely used for national and international statistics for Green House Gas calculations, and as the budget for this study could not include sophisticated modelling of the emissions. However, it is not without problems using the Danish Normative system for assessing manure composition together with data from IPCC (2006). First of all, the two references are not in accordance regarding

¹ JB3 has a clay content of 5 – 10 %, a silt content < 25 % and a fine sand content <40 %. JB6 has a clay content of 10 – 15 %, a silt content < 30 % and a fine sand content of 40 – 90 %

mass balances and emissions (the loss of C due to CH₄ emissions in IPCC (2006) is not in accordance with the DM loss estimated by DJF (2008b)). Secondly, the data is rather “static”. The Danish Normative system do not specify the retention time in the housing units, the pre-tank or the outdoor storage. Furthermore, there is no specification of the emissions from the pre-tank (it is assumed to be included under “storage”, which is included in the data for outdoor storage in this study).

Results of the impact assessment

It should be emphasised that essential assumptions and data in this report are chosen to represent Danish conditions only. Results cannot be immediately transferred to other countries due to differences in housing systems, retention time for the slurry in the housing units and in the outdoor storage, differences in how the slurry is stored (covered / uncovered), differences in temperatures, slurry composition (due to differences in the feeding of the animals), temperature and other weather conditions (during and after application), soil types and many other factors.

The conclusions are only valid for the preconditions described in this report! For example, differences in application method to the field, uncovered outdoor storage or differences in the slurry composition will significantly affect the results.

Contributions to global warming mainly come from CH₄ from in-housing storage, outdoor storage and from CO₂ and N₂O emissions after application of the slurry to the field. Scientific research is needed in the area.

The contribution to acidification is totally dominated by NH₃ emissions in the housing units, during outdoor storage and after application of the slurry to the field.

Aquatic eutrophication (N) is dominated by N leaching. NH₃ emissions also contribute to some extent (contributions from the indoor storage are due to NH₃ emissions).

The results for aquatic phosphorous eutrophication (P) are affected by huge uncertainty, and the results should be interpreted with care. Accordingly it *cannot* be concluded that there is a “net saving on P leaching” by applying pig slurry or dairy cow slurry! The discussion of P leaching from slurry vs. mineral fertilisers is beyond the scope of this study.

The main contributor to ozone formation is the CH₄ emissions from the in-house storage of slurry and the outdoor storage of slurry.

The contributions to the impact “Respiratory inorganics” are totally dominated by contributions from NH₃.

The electricity consumption (for pumps and stirring) is rather insignificant (but for resource consumption).

Transport has a small contribution to the category “Resource consumption” due to the fuel consumption. The contributions to the impact “Photochemical ozone formation” are rather small, and so are the contributions to the category “Respiratory inorganics” (caused by small particles emitted during driving). Transport is totally insignificant for the rest of the impact categories.

The difference between soil type JB3 and JB6 is only noteworthy for aquatic eutrophication (N) (nitrate leaching).

Scenario for the Infarm NH₄⁺ acidification of slurry

Goal

A comparative life cycle assessment has been performed in to answer the question: “What are the environmental benefits and disadvantages of acidification of slurry in the Infarm NH₄⁺ plant compared to the reference scenario for slurry?”. This is done by comparing the environmental impacts from the scenario for acidification of slurry in the Infarm NH₄⁺ plant to the environmental impacts from the reference scenario.

The environmental impacts and conclusions in this chapter build to a great extent on data and information delivered by the producer of the technology, Infarm, or on data made for Infarm. The conclusions rely on this information, and the authors have not had the possibility of verifying the data.

System description

In the Infarm NH₄⁺ Acidification plant, pig or cattle slurry is acidified by the addition of sulphuric acid (H₂SO₄). The sulphuric acid reduces the pH and the chemical equilibrium between ammonium (NH₄⁺) and ammonia (NH₃) is changed which means that it is primarily in the form of ammonium (NH₄⁺). As only ammonia (NH₃) evaporates, the pH of the slurry is a determining factor for the amount of nitrogen / ammonia that volatilize in the housing system, during storage and during application to fields. Moreover, acidification of the slurry has significance for other factors; for example might the use of sulphuric acid for the acidification be an advantage as it adds sulphur to the field which can have a fertiliser effect.

Results of the impact assessment

The results of the comparative life cycle assessment show that:

- Acidification of slurry reduces the NH₃ emissions significantly. As NH₃ gives the main contributions to the environmental impact categories “Acidification” and “Respiratory inorganics”, the total contributions to these are reduced considerably when comparing the acidification scenario to the reference. The contribution to “Acidification” is reduced by 40-90% compared to the contribution from the reference system for pig slurry and by 30-66% compared to the contribution from the reference system for dairy cow slurry. The contribution to “Respiratory inorganics” is reduced by 30-90% compared to the contribution from the reference system for pig slurry and by 20-70% compared to the contribution from the reference system for dairy cow slurry.
- Acidification of slurry reduces the CH₄ emissions, probably due to that the biological activity is inhibited at the low pH. This leads to a reduction of the contributions to the environmental impacts “Global warming and “Photochemical ozone formation”. The contribution to

“Global warming” is reduced by 10-36% compared to the contribution from the reference systems for pig and dairy cow slurry.

- As the acidified slurry contains more N when applied to fields than untreated slurry (due to the reduced losses of NH_3 during storage), the contribution to nitrate leaching is higher for acidified slurry. The higher amount of N will lead to a higher crop yield. When comparing systems in life cycle assessments, it is very important that the outputs of the compared systems are equal (otherwise they are not comparable. For example, a system that produces 1 kg wheat shall not be compared to a system that produces 1 kg wheat plus 2 kg rye). In order to make the system for acidification of slurry equal to the reference system, a corresponding amount of crop yield has been subtracted from the system, which will to some extent counterbalance the higher nitrate leaching (however, these data are rather uncertain). When taking the replaced crop yield into consideration, there is no significant difference between the acidification scenario and the reference scenario on a 10 year basis due to uncertainties. On a 100 year basis, the contribution to nitrate leaching is increased by 10-30% when comparing with the contribution from the reference system.
- Acidification of slurry does not affect “Aquatic phosphorous eutrophication” or the resource consumption of phosphorus, as acidification does not affect the content of phosphorus in the slurry.
- The consumption of non-renewable energy resources is not significantly higher for the acidification scenario as the extra consumption due to the electricity consumption is counterbalanced by the subtraction of the higher crop yield, as explained above.
- The difference between soil type JB3 and JB6 is only noteworthy for aquatic eutrophication (N) (nitrate leaching). The difference is not significant for the overall results.

Scenario for the Samson Bimatech Energy Plant

Goal

A comparative Life Cycle Assessment has been performed in order to answer the question: “What are the environmental benefits and disadvantages of utilising pig slurry for producing fibre pellets in a Samson Bimatech Plant MaNergy 225 and utilising the fibre pellets for heat production - compared to the reference scenario for pig slurry?”.

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

System description

The fibre pellets are produced in a number of steps, which include mechanical separation of pig (or cattle) slurry, drying of the fibre fraction and pressing the dried fibres into pellets. The pellets can be used for heat production at the farm in a Samson Bimatech Energy Plant. The drying process of the wet fibres requires heat and this consumes approximately 40% of the energy produced by combustion of the fibre pellets. The produced heat replaces heat production by light fuel oil (or by the use of straw or wooden pellets in the sensitivity analysis) and the “replaced heat” is subtracted from the system.

The assessment includes pig slurry only, as measurement for cattle slurry was not available at the time of collecting data. Data on cattle slurry has been collected just before finalizing the project (May 2009) however, it was not possible to include this within the time frames of this study.

Results of the impact assessment

The results of the Life Cycle Assessment show that:

The overall contributions to global warming for the system with the Energy Plant are at the same level as the contributions from the reference system (when keeping the high uncertainty on the data in mind). The CO₂ emissions from the combustion of fibre pellets from the Energy Plant is partly counterbalanced by the reduced CO₂ emissions from applying the liquid fraction to field (compared to applying untreated slurry to field) and the CO₂ emissions from the replaced heat production (the Energy Plant produces heat that can be utilized for heating the farmer’s private house. The energy that would have been used for heating the farmer’s house has been subtracted from the system).

The NH₃ emissions is reduced in the Energy Plant scenario compared to the reference scenario due to reduced NH₃ emissions from the application of the liquid fraction to field compared to untreated slurry in the reference scenario. The reduced NH₃ emissions lead to a small reduction in the overall contributions to the environmental impact “Acidification”.

The contribution to aquatic eutrophication (N) is slightly reduced for the Energy Plant scenario, as a smaller total amount of N from the slurry ends at the field because some of the N is removed to the fibre fraction, converted to fiber pellets and combusted.

The contribution to aquatic eutrophication (P) is unchanged.

The scenario for the Energy Plant has a higher contribution to the environmental impact category “photochemical ozone formation” due to emissions of nitrogen oxides during the combustion of the fibre pellets. This is only partly counterbalanced by a slight decrease of CH₄ emissions from the outdoor storage of the liquid fraction compared to the outdoor storage of the reference slurry due to a lower content of C a in the liquid fraction. There are significant uncertainties on the emissions of nitrogen oxides from the Energy Plant due to the fact that the technology is undertaking ongoing product development.

The contribution to the impact category “respiratory inorganics” is at the same level for the scenario with the Energy Plant as for the reference scenario (taking the uncertainties into consideration). The Energy Plant scenario has increased contributions to respiratory inorganics caused by the emissions of nitrogen oxides (and partly by the emissions of particles). The nitrogen oxides are discussed above. However, the contributions from the field processes are lower for the Energy Plant scenario than for the reference scenario due to the reductions of NH_3 as explained above.

The Energy Plant technology is undergoing continuous product development and the technology should be seen as being “in its child-hood”. On one hand it means that it has been difficult to obtain “high quality data” on air emissions and separation indexes. The data on air emissions has significant influence on the nitrogen oxide emissions. On the other hand it probably means that there are plenty of possibilities for improving the technology. The NO_x emissions could probably be reduced significantly by implementing known NO_x reducing technology in the Energy Plant. The separation has huge influence on the overall environmental impacts, as the main contributions come from storage and application of the liquid fraction to field – which to a great extent depend on the proportion of N and C transferred to the fibre fraction. For the mechanical separation, 29.6% of the DM and 6.8% of N is transferred to the fibre fraction (see table C.2). This means that 70.4% of the DM and 93.2% of the N stays in the liquid fraction. Increasing the part of DM and N that is separated to the fibre fraction during the separation by “product development” would reduce the overall environmental performance of the system.

Scenario for fibre pellets used as fertiliser

Goal

A comparative Life Cycle Assessment has been performed in order to answer the question: “What are the environmental benefits and disadvantages of utilising pig slurry for producing fibre pellets in a Samson Bimatech Energy Plant and utilising the fibre pellets for fertilising the field - compared to the reference scenario for pig slurry?”.

The environmental impacts and conclusions in this chapter build to a great extent on data and information delivered by the producer of the technology, Samson Bimatech and on data made for Samson Bimatech (laboratory measurements of the slurry composition). The conclusions rely on this information, and the authors do not have had the possibility of verifying the data.

System description

The system in this chapter is very alike the system for the “Energy Plant scenario” mentioned above. However, the fibre pellets are not used for heat production as the “Energy Plant scenario”, but for application to the field as fertiliser.

It should be emphasised that this scenario is mostly performed as “a test of a future possibility”, as fibre pellets are not used for fertilising today.

Results of the impact assessment

When keeping the overall uncertainty on the data in mind, there is no significant difference between the overall contributions to global warming, aquatic eutrophication (P), “respiratory inorganics” and the consumption of phosphorus as a resource when comparing the “Fibre Pellets used for fertilising”-scenario compared to the reference system.

The “Fibre Pellets used for fertilising”-scenario has a slightly reduced contribution to the environmental impact “Acidification” and to aquatic eutrophication (N) than the reference system due to the reduced NH_3 emissions and N leaching from the liquid fraction applied to field compared to untreated slurry.

The contribution to “photochemical ozone formation” is slightly higher from the “Fibre Pellets used for fertilising”-scenario compared to the reference system.

The consumption of non-renewable energy resources is considerably higher caused by the electricity consumption by the Energy Plant.

1 Introduction and objectives

1.1 Background

In 2007, the Danish government launched an action plan to promote eco-efficient technology. The aim was to support the development of competitive technologies which benefit the environment and Danish business. As a part of the action plan, partnerships for innovation were established in five selected areas, among these “Partnership for Industrial Biotechnology”. Furthermore, the action plan included focus on Eco-efficient agricultural technologies.

On the background of the ongoing work in Partnership for Industrial Biotechnology combined with the fact that years of Danish research in the agricultural area has generated huge amount of environmental data for slurry management, the Danish Environmental Agency decided to initiate the preparation of a foundation for Life Cycle Assessment (LCA) for slurry management technologies.

At present, the existing environmental data for slurry management has not been collected systematically, which is required for the LCA-modelling of the environmental impacts of slurry management technologies.

The companies and organisations in Partnership for Industrial Biotechnology have agreed with the Danish Environmental Protection Agency to initiate this project in order to be able to establish a LCA foundation for slurry management. The contributing companies in this project have decided to put their own data on processes, mass balances and emissions at the disposal.

1.2 Objectives of the study

The objective of this study is to establish a foundation for Life Cycle Assessments of slurry management technologies in Denmark.

The LCA foundation consists of:

- A database containing Life Cycle Data for selected slurry management technologies,
- A reference model for conventional slurry management, which is expanded with models for alternative technologies and data from the contribution of participating companies. The models are part of the database.
- This report, containing examples and results of Life Cycle Assessments performed for selected slurry management technologies.

The LCA foundation can be used by the contributing companies for evaluating the environmental sustainability of a specific technology from a holistic Life Cycle perspective. The goal of the study is to answer the question for each alternative technology: “What are the environmental benefits and disadvantages of introducing this technology for slurry management?”

From a societal perspective the results can contribute to a clarification of which slurry management technologies (or combination of technologies) having the largest potential for reducing the overall environmental impacts.

Moreover, some of the partners from Partnership for Industrial Biotechnology have mentioned that the results might be used in the work on EU standardization and certification in the area.

The results of the study are intended for public disclosure.

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 June 2008 - June 2009 for a budget corresponding to 3 months of fulltime work.

The steering committee for the study included:

- Peter H. Schaarup, Environmental Protection Agency of Denmark
- Thomas Alstrup, FORA
- Frank Rosager, Xergi A/S
- Michael Stöckler, Agro Business Park
- Jesper Kløverpris, Novozymes
- Gunnar Hald Mikkelsen, Samson-Agro A/S
- Morten Nørager, Kemira Water A/S
- Jens Lund Pedersen Kemira Water A/S
- Thorbjørn Machholm, Grundfos Management A/S

Furthermore, significant contributions was received from

- Jørgen Mertz, Samson-Bimatech A/S
- Nils Thorup, Grundfos Management A/S
- Jesper Ravn Lorenzen, Grundfos New Business A/S
- Lene Venke Kofod, Novozymes

The technical advisory group for the study included:

- Sven Sommer, University of Southern Denmark
- Randi Dalgaard, Danish Crown
- Bjørn Molt Petersen, Department of Agroecology and Environment, Faculty of Agricultural Sciences, Aarhus University
- Søren O. Petersen, Department of Agroecology and Environment, Faculty of Agricultural Sciences, Aarhus University

The study has been carried out by the University of Southern Denmark.

2 Scope

2.1 Methodology

The environmental assessment in this study is based on the method for Life Cycle Assessments (LCA) described in the Danish EDIP method by Wenzel et al. (1997) and further updates of this method (Weidema et al. (2004), Weidema (2004), Stranddorf et al. (2005)).

Life Cycle Assessment is the assessment of the environmental impacts of a product (or service) throughout its lifespan, i.e. “from cradle to grave”. That means that the environmental impacts are followed through the whole product chain, typically from raw material extraction, through production and use, to final disposal or recycling. For agricultural products, the chain would include fertiliser production, grain production, field activities for crops, animal husbandry, slurry management, transport, storage, preparation of food and food products disposed in the households.

The method used in this study is in agreement with the standards of the International Organisation for Standardisation, ISO (ISO 14040 (2006) and ISO 14044 (2006)), except that an external review has not been performed by an external LCA review panel as required by the ISO standards, as a LCA review panel was not included in the budget for the study.

The study is comparative, as environmental impacts of the new technologies are compared to the reference scenarios. This is mentioned since the ISO 14040 and 14044 standards for Life Cycle Assessment include specific requirements for comparative Life Cycle Assessments that are disclosed to the public, among these special requirements regarding a LCA review panel.

The primary data for the technologies in this study are delivered by the producers of the technologies. Background data are from the Ecoinvent database. Ecoinvent is the world's leading supplier of consistent and transparent life cycle inventory data (The Ecoinvent Centre, 2008). The database from the project will be available in SimaPro format and use requires license to SimaPro and Ecoinvent. The LCA has been performed by the use of the PC-tool SimaPro 7.1, which is the most widely used LCA software today (PRé, 2008).

2.2 Reference scenarios and alternatives

In this study, the reference scenarios are:

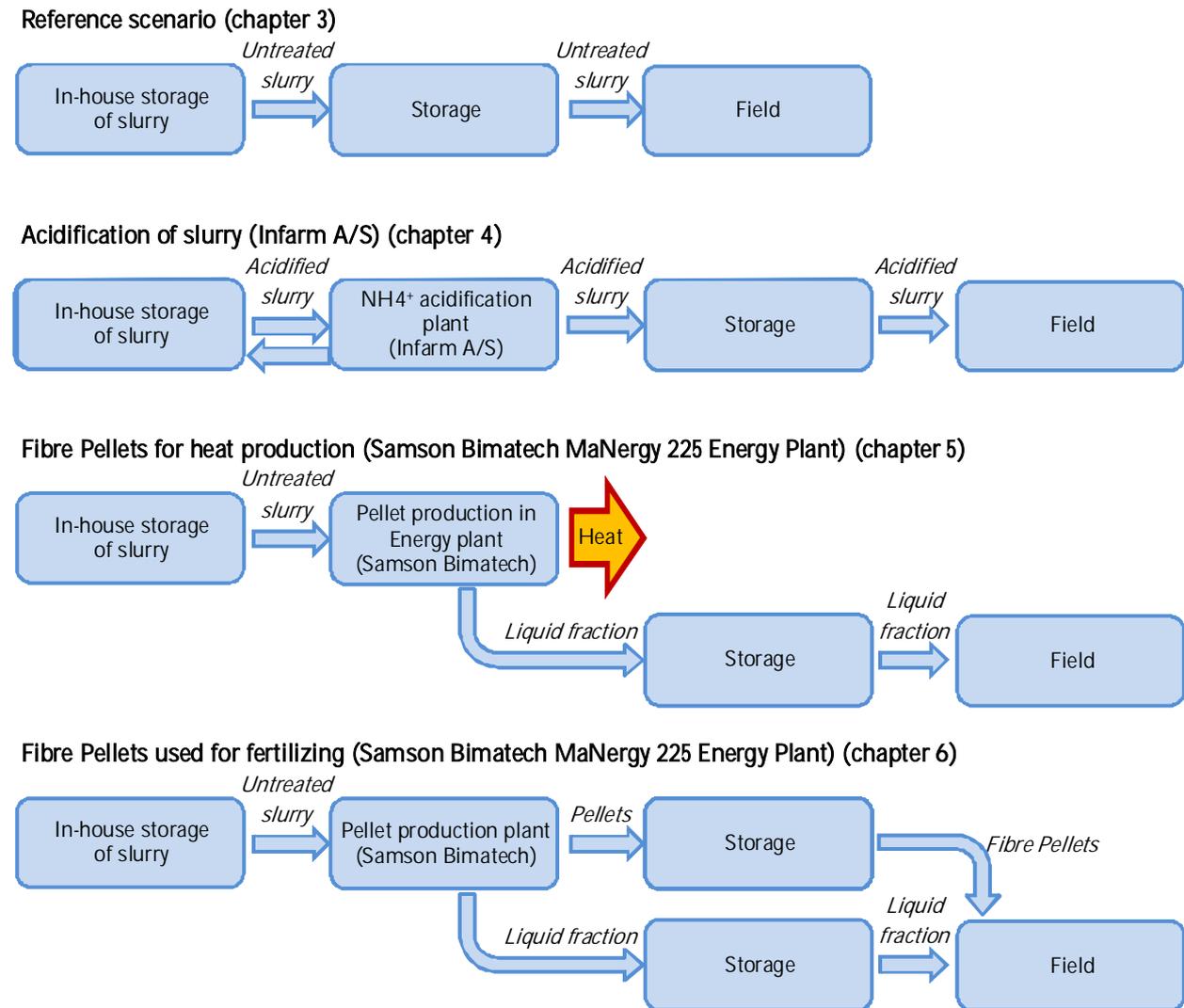
- Slurry from *fattening pigs*, stored in the slurry pits below the animals in the housing units, stored in a concrete slurry tank (covered by a natural floating layer), transported and applied to field.
- Slurry from *dairy cows*, stored in the slurry pits below the animals in the housing units, stored in a concrete slurry tank (covered by a natural floating layer), transported and applied to field.

A detailed description of the reference scenarios are specified in chapter 3.

The reference scenarios serve as a basis for the assessment of the environmental impacts of the alternative technologies for slurry management, and combinations of these. The environmental consequences of choosing alternative technologies are compared to the reference scenarios.

The alternative technologies included in this study are shown in the flow-diagrams in figure 2.1 below. It must be noticed that the flow diagrams are very rough and simplified in order to present an overview.

Figure 2.1.
Overview of the slurry treatment technologies included in this study.



As it can be seen from figure 2.1, the slurry treatment technologies included in this report are:

- Acidification of slurry and subsequent storage and application of the acidified slurry to field (Infarm NH₄⁺ plant).
- Mechanical separation of slurry into a fibre fraction and a liquid fraction (Samson Bimatech Separation plant):

- Use of the fibre fraction for fibre pellets production and use of the pellets for:
 - Application to field
 - Heat production in a Samson Bimatech Energy Plant
- Application of the liquid fraction directly to the field

The reference scenario is described in chapter 3, and the data for the life cycle assessment is outlined in Annex A.

Acidification of slurry in the Infarm NH₄⁺ plant is described in chapter 4, and the data for the life cycle assessment is outlined in Annex B.

In the Samson Bimatech MaNergy 225 Energy Plant pig slurry is mechanically separated and the fibre fraction is used for producing fibre pellets. The fibre pellets are combusted for producing energy for the farm. This scenario is described in chapter 5. The data for the life cycle assessment for the mechanical separation (which is part of the Samson Bimatech MaNergy 225 Energy Plant) is described in Annex C. The data for the life cycle assessment Samson Bimatech MaNergy 225 Energy Plant is described in Annex D.

The fibre pellets from the Samson Bimatech MaNergy 225 Energy can be used for fertilising. This scenario is described in chapter 6. The data for the life cycle assessment can be found in Annex E (combined with data from Annex C and D).

For a fully understanding of the preconditions and the systems, reading of the Annexes is required.

There is a huge variety of alternative technologies for slurry management. It has not been possible to include all of these various alternatives within the framework of this study. For example, it has not been possible to include the environmental impacts of changed diet for the animals, the use of enzymes in the feed, the changed management of the slurry in the housing system or the various technologies for application of slurry to the field. The exclusion should *not* be seen as these technologies are regarded as unimportant – some of them most likely have huge significance for the overall environmental impacts – they are only excluded due to the time and budget constraints of the project.

Biogas production will be included in an upcoming report.

2.3 Consequential approach

This study is conducted according to the principles of consequential LCA. The consequential LCA approach was developed during the Danish consensus project on Life Cycle Assessment in 1997-2003 (Hansen, 2007). The consequential approach is described in Weidema (2004). The ISO standards for Life Cycle Assessment (ISO 14040 and ISO 14044) recommends expanding the product system to include the additional functions related to the co-products, which is the same as the consequential

approach². In the next version of the world's leading LCA database, Ecoinvent, the consequential approach will be the default method (Weidema, 2009)³.

The consequential approach should be used when the goal of the study is to identify the environmental consequence of choosing one alternative over the other or, in this study, the consequence of choosing a new technology as a replacement for the conventional slurry management methods.

The consequential approach requires that the LCA is comparative, i.e. that alternatives are compared. The consequential and comparative approach ensures that all compared alternatives are equivalent and provide the same services to society, not just regarding the primary service, which is the "main function" of the system, but also on all secondary services. Secondary services are defined as products/services arising e.g. as co-products from processes in the studied systems. In this study, secondary functions are for example the nutrient value of the slurry (that can replace mineral fertilisers) or the energy content of the biogas produced from the slurry (replacing other energy production).

The consequential LCA ensures equivalence on all primary and secondary services by identifying and including the displacements of alternative products that will occur when choosing one alternative over the other. See further explanation of comparative and consequential LCA in Wenzel (1998), Ekvall and Weidema (2004) and Weidema (2004).

In order to make a reasonable comparison it is fundamental to perform the assessment in relation to the same function, i.e. the same service, which is in Life Cycle methodology called "the Functional Unit".

2.4 Basis for the comparison: The functional unit

The primary service of all the scenarios is defined as: "Management of slurry", which includes various kind of treatment and utilization of slurry.

The functional unit is: "Management of 1000 kg slurry".

The reference flow is defined as 1000 kg slurry "ex animal", i.e. right after excretion. The composition of the reference slurry is further specified in section 3.2 below.

² In the ISO standards for Life Cycle Assessment (ISO 14040 and ISO 14044), the first recommended step under "Allocation procedure" is to avoid allocation by dividing the unit processes into sub-processes (which means that allocation is not necessary), and, if this is not possible, to avoid allocation by expanding the product system to include the additional functions related to the co-products, which is the same as the consequential approach.

³ Statement from Bo Weidema, Executive Manager for the Ecoinvent Database, 2009: "We plan to improve the database with the release of version 3, which will be available in two standard versions: One is a consequential version where the inputs to each process are the ones affected on long-term by a small change in demand, and where all co-products are treated by system expansion. In addition to this consequential version, the Ecoinvent database will also be available in an attributional version where the inputs to each process are the current average suppliers, and where all co-products are treated by economic allocation."

All the scenarios in this study have additional secondary services. These are described under each scenario in chapter 3-6.

2.5 System boundaries

In principle, all environmental impacts from all processes in the entire chain have to be included; however, when comparing alternatives, it is not necessary to include processes that are identical in the compared systems.

In this study, focus has been put on the differences, and the processes, that are identical for the reference scenarios and the alternative technologies have been left out.

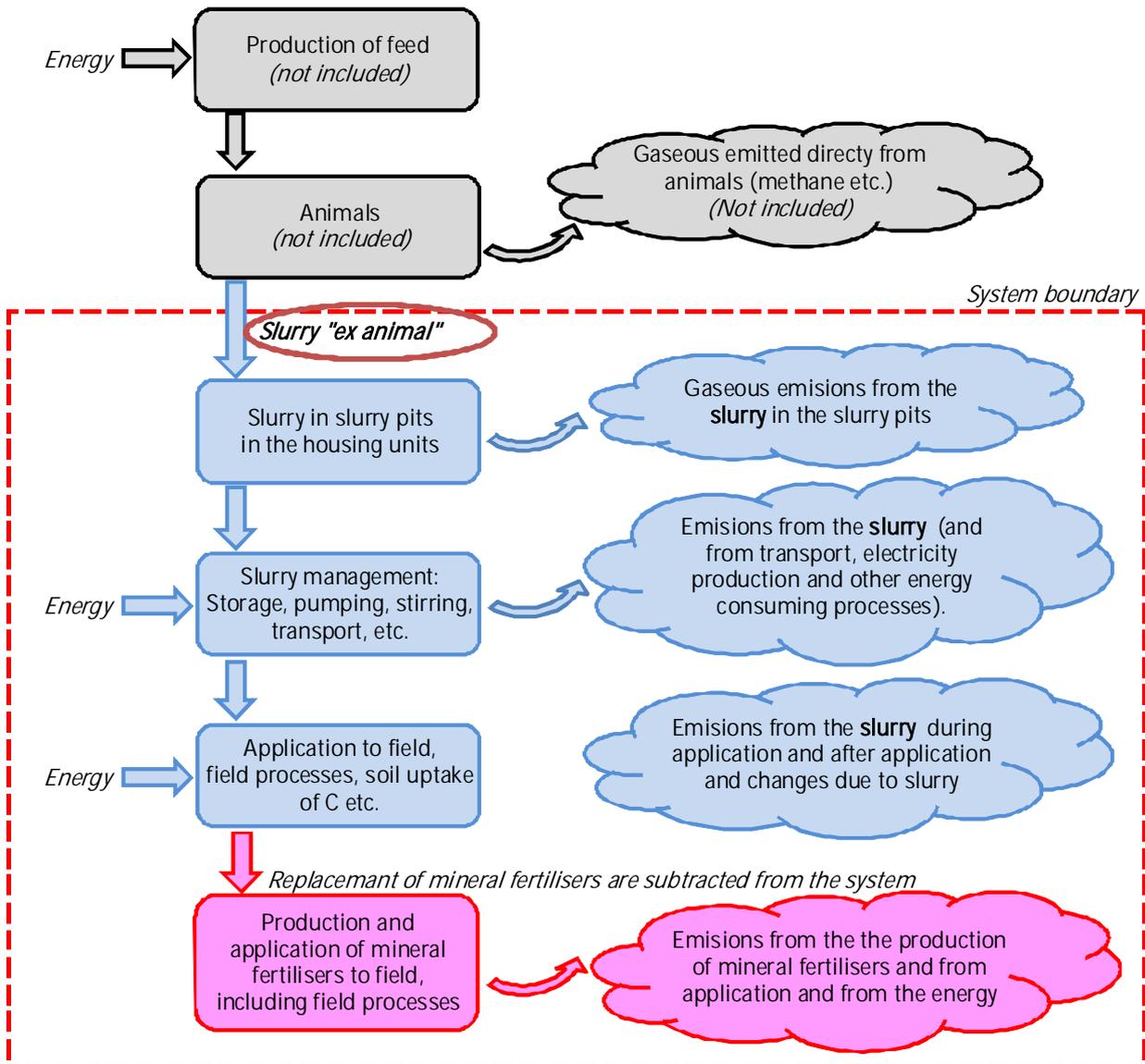
Common for all the scenarios in this study are all the processes “upstream” of the slurry excretion, i.e. production of pigs and cattle, production of feed, medicine, hormones, housing systems etc. Also the energy consumption within the housing system is assumed to be the same, and all common processes are excluded. Furthermore, methane emissions from the cattle in the housing units are *not* included. These are left out as they are identical in all scenarios, but also as they are not relevant for the goal of the study (“What are the environmental benefits and disadvantages of introducing slurry management technology X?”). The starting point is, thus, the slurry excreted in the housing units. In other words, the system starts when the slurry leaves the pig or the cow and hits the floor or the slurry pits in the housing system, see figure 2.2.

As can be seen from figure 2.2, gaseous emissions (methane, carbon dioxide) from the animals are *not* included within the system boundaries (as changed slurry management has no influence on the enteric fermentation and on the respiration).

Included are only the gaseous emissions from the *slurry* and the emissions from all the slurry management that follows; in-house handling, pumping, storage, transport and application to the field. These are the focus of this report.

Figure 2.2.

System boundaries: The blue coloured processes and emissions are within the system boundaries and these are included in this study. The grey processes and emissions are *not* included.



It is not claimed that the processes "upstream" (i.e. before the slurry excretion) have no environmental significance - it is just without the frame of this study. Other studies that have dealt with the whole food chain in an LCA perspective have concluded that the slurry management part is significant for the overall environmental impacts of meat production. Dalgaard (2007) concluded a life cycle assessment for pork production and Weidema et al. (2008) included the whole life cycle for pigs and cattle in a study entitled "Environmental Improvement Potentials of Meat and Dairy Products". In both studies, it is concluded that the slurry and slurry management have overall significance especially for the environmental impact categories "acidification" and "eutrophication". Dalgaard (2007) states that ammonia from the farms contributes to 83% of the acidification substances emitted from the product chain of Danish pork, and 70% of this is caused by slurry emissions in the housing system, storage and during application. When considering the whole product chain of pork, the two largest contributors to

eutrophication were nitrate (63%) and ammonia (30%). According to Nielsen et al. (2008b), the agricultural sector contributed with 14% of the overall greenhouse gas emission (in CO₂ equivalents) in 2006.

The emissions of CH₄ and N₂O from *manure management* contributed with 16% of the total emission from the agricultural sector in 2006.

According to the system boundaries in this study, the major part of the agricultural CH₄ emission originates from digestive processes (i.e. enteric fermentation) is *not* included in this report (as it is not affected by different types of management of the manure. This accounted for 27% of the total contribution to global warming from agricultural activities in 2006.

Included within the system boundaries for the reference scenario are emissions from the slurry in the housing units and in the pre-tank, outdoor storage, transport, application to field, avoided / reduced production of mineral fertilisers due to the fertiliser value of the slurry and organic matter incorporation in the soil which include carbon sequestration. A flow diagram for the reference scenario is shown in figure 3.1 in chapter 3.

In principle, the crops on the field are not included within the system boundaries. However, it has been necessary to include small amounts of “increased crop production” for some of the new technologies when the slurry management actually leads to an increase of the crop yield. This is elaborated later. In order to specify the emissions from the field, a reference crop rotation for pig farms and cattle farms has been set up in the system description in section 3.1. This has been necessary in order to estimate the input and output from the fields.

The energy consumption for all the slurry management technologies is included, for example the energy consumption for pumping, for the separation processes or for transport.

The energy consumption in the housing units is generally not included, however, the *extra* energy consumption for the “add-on” technology in the housing system is included, for example the consumption of energy / chemicals for acidification of the slurry in the housing units is taken into account.

In principle, all emissions and flows with significant environmental impact have to be included in a life cycle assessment. In case of lack of data, estimates have been made rather than leaving gaps.

For all the slurry management technologies, the total life cycle of the technology is included as far as possible. However, if some parts of the life cycle have shown to be insignificant for the overall environmental impacts, they have been left out. Data for equipment, machinery, and maintenance is included, primarily based on estimates or literature data.

It has not been possible to include data for “overhead activities” (i.e. office expenses, heating of offices, transport of employees to and from work for the plants producing the technologies etc). It is estimated that this omission is of minor significance for the overall results, as it is only the relative differences between the scenarios that should be included anyway.

Furthermore, all the processes “behind” this system 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, production of materials and electricity production. The system “behind” the product chain for slurry management is huge with hundreds of processes.

In some Life Cycle Assessments, biogenic carbon dioxide (CO₂) is not included as it is regarded as “neutral” (Crops take up CO₂ when growing, and when the crop is incinerated, the CO₂ ends back in the environment). In this Life Cycle Assessment biogenic CO₂ is included. First of all, biogenic CO₂ contributes exactly as much to global warming as CO₂ from fossil fuels. Secondly, it is very important for the results of this study to identify how much of the carbon applied to the soil that will be incorporated in the soil and how much that is emitted as CO₂. As the amount of biogenic CO₂ emissions are different from the various technologies, it is important to include the biogenic CO₂ and the global warming potential caused by it. In this way, the difference between the biogenic CO₂ and the C stored in the soil is included in the comparison between the reference scenario and the scenarios for each of the new technologies.

It should be emphasized that the Life Cycle Assessment methodology is a simplified model of the environmental impacts. A lot of the processes in the slurry management chain are complex and dependent upon many variables, especially the field processes. The simplified Life Cycle Assessment methodology is not capable of handling dynamic modelling. In LCA, these dynamic data are translated into a set of discrete parameters and values that are carefully chosen in order to represent the situation as well as possible (as done in section 3 when defining the reference scenarios), and these parameters can be changed for analysing the uncertainty. However, LCA is not suitable as e.g. a dynamic model for the analysis of the development during the next 10-20 years, showing the results year by year.

2.6 Temporal, geographical and technological coverage

The study has been based on data from the most recent year for which consistent data are available. It is the intention, that data used for this study should apply for 2008 and 5-7 years ahead. As most 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 (for example the pig and cattle housing systems are typically Danish, so are the storage facilities, soil types and energy production). 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). The soil conditions and application of fertilisers are also different in Denmark compared to other European countries. Accordingly, it is not possible to transfer the results directly to other European countries without adjustments.

The intended technology level for the reference scenario is to set up a “typical Danish scenario”, based on “average technology”. The scenario should represent “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 environmental impact categories in this study are primarily based on the Danish EDIP method. Not all impact categories from the EDIP method has been included, see table 2.1.

Note, that all the 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; however, the larger concern is usually the subsequent damages to humans, animals and plants. Global warming have 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. Accordingly, it is not within the frame of the LCA method 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 14040 and ISO 14044) and international consensus, acknowledging that it is in practice impossible to know all sites of 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 (CO₂), methane (CH₄) and nitrous oxide (N₂O).
- *Acidification*, which causes damage to forest, other vegetation and lakes. The primary contributors to acidification are sulphur oxides (SO₂ and SO₃), nitrogen oxides (NO_x) and ammonia (NH₃). For agriculture especially ammonia emissions are in focus.
- *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 phosphorus (P). 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)” and “Aquatic eutrophication (P)” has 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 NH₃ for the scenarios included in this study).

- *Photochemical ozone formation (“smog”)*, which is caused by reactive compounds forming ozone on the lower layer of the atmosphere, i.e. at the human breathable level, causing respiratory problems for humans and potentially reducing growth of crops. It is commonly known as “smog” in large cities. The main contributors are nitrogen oxides (NO_x), volatile organic compounds (VOC) (including methane (CH₄)) 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 “Ozone formation, impacts on humans” has been included (representing both).

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 from the media. Also impacts from ammonia, nitrogen oxides and sulphur dioxide are included in this category. Airborne ammonia attaches to other airborne emissions forms small particulates that are regarded as harmful to health when inhaled (Hansen et al., 2008). 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). In the Impact 2002+ method, particulates are assessed according to size (PM₁₀ are particulates with a diameter of < 10 µm and PM_{2.5} have a diameter < 2.5 µm).
- *Phosphorus* (as a resource) has been chosen as a separate impact indicator category in addition to the general resource calculations in the EDIP method, as the phosphorus resource issue and recycling of phosphorus is particularly relevant for this project. Phosphorus is an essential element for plant and animal nutrition. In case of depletion there could be a serious problem for the global food production since phosphorus is such an essential ingredient in fertilisers, especially because 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). A significant reduction in the global crop production that would occur without phosphorus fertilisation combined with a massive increase in the world population could lead to hunger and starvation. The normalisation factor in this study is based on Nielsen and Wenzel (2005).
- *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+, which is mentioned above (Humbert et al. 2005). The unit is “MJ Primary Energy”, using the upper heating value.

An attempt to include odour as a separate impact indicator category has been made. Odour is often a problem for traditional slurry management and some of the alternative technologies are designed specifically to handle odour problems. However, the inclusion of odour is not simple. The definition of where the odour measurements should be taken can be discussed. It is probably more the neighbours of the (pig) farm that are 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 $100 \cdot 10^6$ OU_E for 5 days might be worse than an odour of $500 \cdot 10^6$ 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. It has been decided not to include quantitative data on odour, and odour is not included as an impact category in this study. For odour reducing technologies, the reduction is described qualitatively. The database has however been prepared for including odour at a later stage.

With regard to the aspects of slurry management, it would have been obvious to include indicators on spreading of biological contamination (spreading of bacteria and virus), hormones and medicine residues. For instance, the aspects of penicillin and resistance are widely debated. However, it has not been possible to find adequate quantitative data on these aspects; thus, they will be included qualitatively in the discussion.

Table 2.1.
Included and excluded impact categories.

Included impact categories	
Global warming (climate change)	The EDIP 2003 method (Hauschild et al., 2005) (based on the Danish EDIP 1997 method and update of this by Stranddorf et al. (2005)).
Acidification	The EDIP 2003 method (Hauschild et al., 2005) and Potting et al. (2005)
Aquatic Eutrophication (N)	The EDIP 2003 method (Hauschild et al., 2005) and Potting et al. (2005)
Aquatic Eutrophication (P)	The EDIP 2003 method (Hauschild et al., 2005) and Potting et al. (2005)
Photochemical ozone formation ("smog")	The EDIP 2003 method (Hauschild et al., 2005) and Potting 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. Relevant for transport and combustion processes and relevant with regard to ammonia, see text above.
Non-renewable energy resources	From the Impact 2002+ method. The unit is "MJ Primary Energy", using the upper heating value.
Phosphorus	Chosen as special resource indicator as the recycling issue of phosphorus is particularly relevant for this project.
Impact categories NOT included	
Stratospheric Ozone depletion	Considered insignificant in relation to the chain for slurry management
Terrestrial eutrophication	From the EDIP 2003 method (Hauschild et al., 2005) and Potting et al. (2005) – excluded 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
Toxicity	Toxicity in the slurry management chain could be relevant regarding pesticides, hormones, medicine remains and spreading of Cu and Zn. 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.
Odour	It has not been possible to include quantitative data for these categories, see text above. Accordingly, it has been decided to include them in a qualitative discussion instead, where relevant. 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 2.2 shows the main emissions that contribute to the impact assessment categories mentioned in table 2.1. According to Sleeswijk et al. (2008), 10 emissions fully dominate the contributions to the non-toxic emission dependent environmental impacts in Life Cycle Assessments: CO₂, CH₄, SO₂, NO_x, NH₃, PM₁₀, NMVOC, and (H)CFCs emissions to air and emissions of N- and P-compounds to fresh water. 9 of these are included in this study

remaining emission category, (H)CFCs, is considered not relevant for slurry management technologies, accordingly, it is not included (but not left out by principal either. Simply they do not occur for any of the technologies). In addition to the emissions recommended by Sleeswijk et al. (2008), N₂O has been included, as this is especially relevant for agricultural systems.

The emissions in table 2.2 have been included for all the “foreground processes” as far as possible (i.e. for all the processes regarding slurry management that the data have been collected for in this study). The “background processes” from the Ecoinvent database contains far more emissions than these.

Table 2.2.

the emissions that data are collected for the “foreground processes” in this study.

Air emissions included in this study	Impact categories affected by the emissions
Carbon dioxide (CO ₂)	<ul style="list-style-type: none"> • Global warming
Carbon monoxide (CO)	<ul style="list-style-type: none"> • Photochemical ozone formation (“smog”) • Global warming • Respiratory inorganics / Respiratory problems
Methane (CH ₄)	<ul style="list-style-type: none"> • Global warming • Photochemical ozone formation (“smog”)
Non-methane volatile organic compounds (NMVOC)	<ul style="list-style-type: none"> • Photochemical ozone formation (“smog”)
Ammonia (NH ₃ -N)	<ul style="list-style-type: none"> • Acidification • Eutrophication (nutrient enrichment) • Respiratory inorganics /Respiratory problems • (indirectly to Global warming as NH3 gives indirect N2O emissions)
Nitrous oxide (N ₂ O-N)	<ul style="list-style-type: none"> • Global warming • Eutrophication (nutrient enrichment)
Nitrogen oxides (NO _x -N) (including NO ₂ + NO)	<ul style="list-style-type: none"> • 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)	<ul style="list-style-type: none"> • Included in order to establish mass balances
Particulates (PM10)	<ul style="list-style-type: none"> • Respiratory inorganics / Respiratory problems
Sulphur dioxide (SO ₂)	<ul style="list-style-type: none"> • Acidification • Respiratory inorganics / Respiratory problems
<i>(Hydrogen sulphide (H₂S) – it was the intention to include this. In practise it was not possible to find sufficient data)</i>	<ul style="list-style-type: none"> • Human toxicity
Included discharges to water	
Leaching of N (nitrogen) compounds	<ul style="list-style-type: none"> • Eutrophication (nutrient enrichment) • (indirectly to Global warming as leaching gives indirect N2O emissions)
Leaching of P (phosphorous) compounds.	<ul style="list-style-type: none"> • Eutrophication (nutrient enrichment)
Copper (Cu)	<ul style="list-style-type: none"> • Aquatic toxicity
Zinc (Zn)	<ul style="list-style-type: none"> • Aquatic toxicity

* Among the 10 emission categories that have the main contributions to the non-toxic emission dependent environmental impacts according to Sleeswijk et al. (2008)

3 Reference scenarios

3.1 System Description

The reference scenarios in this report do not represent an average of the slurry management systems in Denmark, but should rather be seen as a representative of “typical” systems. Accordingly, an attempt to identify the most commonly used methods has been made. The reference scenarios do not cover all situations and possibilities. For some of the possibilities, sensitivity analyses of different alternatives have been made in order to clarify the significance of the choice.

For pigs, the reference scenario is based on *fattening pigs*. Fattening pigs constitute a significant amount of the total number of pigs in Denmark. According to Statistics Denmark (2008a) approximately 42% of all pigs where “Weaned pigs less than 50 kg” and 28% of all pigs where “Weaned pigs at 50 kg and above” in 2007. Hence, in total 70%⁴ of the pigs in Denmark are fattening pigs (30-100 kg). The Danish Norm data for N, P and K in livestock manure (2001-2008) are all based on the study made by Poulsen et al. (2001), where the category “Fattening pigs (30-100 kg)” is used. The slurry composition for this category has been used in this study.

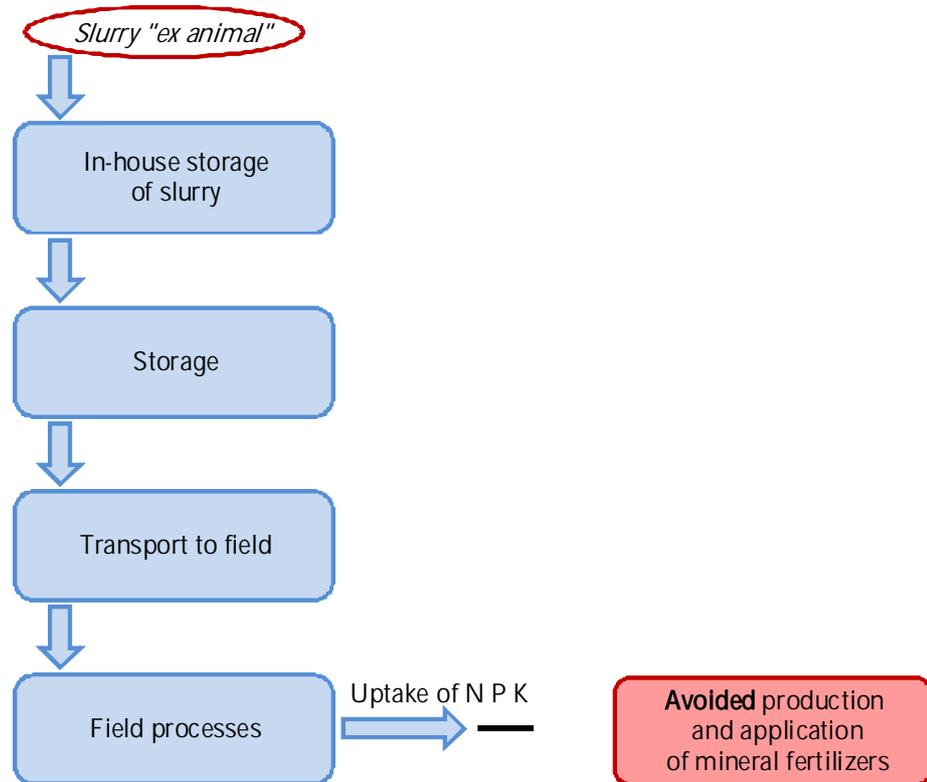
For cattle, it has been decided to base the reference scenario on *dairy cows*. According to Dansk Kvæg (2007 and 2008), *dairy cows* constituted approximately 35% of the cattle livestock population in Denmark in 2007 and 2006. The category “*dairy cows*” was the largest single category. In the Danish Norm data for N, P and K in livestock manure (2001-2008) and in Poulsen et al. (2001), the corresponding category is “1 year cow, heavy race”. (Poulsen et al. (2001) also have a category for Jersey cattle, however, the Jersey cattle production is relatively small according to the statistics in Dansk Kvæg (2007 and 2008)).

The choice of selecting the categories “fattening pigs” and “dairy cows” are supported by the fact that a considerable amount of the international literature in the slurry management area focus on these categories, thus the data availability is considerable for these categories.

A simplified flow diagram for the reference scenarios is shown in figure 3.1

⁴ I.e the 42% pigs in the category “Weaned pigs less than 50 kg” plus the 28% pigs in the category “Weaned pigs at 50 kg and above”.

Figure 3.1.
A simplified flow diagram for the reference scenarios



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. Some of these preconditions are significant for the final results. Hence, sensitivity analysis has been carried out for most of the preconditions in order to estimate the magnitude of the significance.

The main preconditions for the reference scenario for fattening pigs are described below:

- For fattening pigs, the reference scenario is based on a housing system with “*Fully slatted floor*”. This has been chosen due to the fact that fully slatted floor was the most common housing system for fattening pigs in Denmark in 2006-2007 (approximately half of the housing systems for fattening pigs), according to Hanne Damgaard Poulsen (October 2008, personal communication) and Nielsen (2008) (Annex C).
- From the pre-tank in connection with the housing units the slurry is pumped to the outdoor storage.
- It is common practice that the slurry is stored outdoor in concrete slurry tanks and *covered by a floating layer* (Christiansen et al., 2003). In Denmark, it is required by law to cover slurry storages in order to reduce ammonia emissions and odour. When storing cattle slurry, a natural floating layer will normally be created. However, for pig slurry,

a natural floating layer is less likely to occur, and a cover has to be established by the farmer (Rasmussen et al., 2001) and Christiansen et al., 2003). The use of a PVC roof is also becoming more and more common (Personal communication, S Sommer, 2008). The minimum requirement in the law is a floating layer of straw. When establishing new slurry tanks for pig slurry, the requirement in the law is permanent cover (e.g. a PVC roof) if the distance to neighbours is less than 300 metres. For the reference scenario, a floating layer has been chosen (natural for cattle slurry and by cutted straw for pig slurry) as this is the minimum requirement in the law and as this is the cheapest method (Rasmussen et al., 2001). Of course, probably not all farmers respect the minimum requirements, but the reference scenarios do not cover these situations

- The *transport distance* from storage to application to fields has been difficult to estimate. Udesen and Rasmussen (2003) estimate a transport distance of 2 km for farmers applying the slurry to their own fields while Rasmussen and Jørgensen (2003) use an estimate of 5 km. Pedersen (2007) has made a study of transport of slurry based on 8 cases, where the slurry was transported over respectively 0.4 km, 0.7 km, 1 km, 4.3 km, 4.5 km, 10 km, 19 km, 30 km, and 32 km. Feenstra et al. (2003) states, that demands in the Action Plan for the Aquatic Environment III 2005-2015 (Vandmiljøplan III) regarding the distribution of the surplus of phosphorus in slurry will induce that huge amounts of slurry have to be transported from areas with surplus of phosphorus (due to a high livestock density) to areas that need phosphorus. However, Feenstra et al. (2003) give no indication of distances. It has not been possible to find estimates on this increased need for transport. Jacobsen et al. (2002) wrote that there are not many Danish assessments of the transport distances for slurry. In the study by Jacobsen et al. (2002), interviews were carried out, and the interviews seemed to support the assumption that the transport distance usually is below 5 km. They found that an increase in the total slurry amount from 2000 tons of slurry to 6000 tons of slurry increased the transport distance from 700 meters to around 1100 meters. A request at the Danish Environmental Protection Agency indicated that they have no information on the average transport distance for slurry in Denmark (personal communication, K S Andersen, December 2008). Most of the alternative technologies, covered by this report, are primarily relevant for large conventional farms with relatively high livestock densities. Accordingly, it could be argued that the focus of this report should be put on relatively long transport distances. For small distances, it is common to use a tractor with trailer. If the transport of slurry to the fields is more than 10 km, transport by truck is required by law in Denmark. In this report, the calculations are based on a transport distance of 10 km. Furthermore, sensitivity analysis is carried out for transport distances of 2 km and 32 km (as 32 km is the maximum distance found by Pedersen (2007)).
- Pig slurry is applied with *trail hose tankers to the field* in the reference scenarios. According to Landscentret (2008), 68% of all slurry was spread by trail hose application tanker in 2004, and this is still the most common method today (Personal communication with Birkmose (2008) and Pedersen (2008)).

- Relevant *soil types* for pig production and application of pig slurry are clay soil and sandy soil. The LCAfood project (www.lcafood.dk) operates with two types of soil: “clayey soil” (> 10% clay) “sandy soil” (<10% clay). According to Halberg and Nielsen (2003), pig farms on clay soil constituted 29% of the total Danish pig meat production in 1999, and pig farms on sandy soil constituted 49% of the total Danish pig meat production (The remaining of the pig meat production is farmers that have mixed production with less than 10% of the income from pig production plus a small group of organic pig producers). Accordingly, the reference scenario is set up for both clayey soil and sandy soil for pig slurry. In the modelling, soil type JB3 has been used representing sandy soil and soil type JB6 has been used representing clayey soil. JB6 has been chosen because it is the most common soil type with clay > 10%. JB3 has been chosen because it is considered the best representative of sandy soil (JB1 – JB4), where JB2 is fairly rare in Denmark.⁵
- 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. According to statistics from Nehmdahl (2009) on the distribution of crop types for pig farms and cattle farms, the most common crop type for Danish pig farms is winter wheat (36.4%), followed by spring barley (19.2%) and winter barley (19.2%) (data from 2007). This is verified by experts in the area (Birkmose (2008) and Hermansen (2008)). In order to make a reasonable realistic, though simplified, crop rotation for pig farms, a six year rotation was utilised, with slurry N (kg ha⁻¹ y⁻¹) applied 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). According to statistics in Nielsen et al. (2008, page 501), 60% of all slurry in Denmark was applied by trailing hoses in the winter-spring period. It is assumed that the slurry is applied during spring. 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.

The main preconditions for the reference scenario for dairy cows are described below.

- For dairy cows, the reference scenario is based on a “Cubicle housing system with slatted floor (1.2 m channel)”⁶. This has been chosen due to the fact that this housing system was the most common housing system for dairy cows in Denmark in 2006-2007 (slightly less than half of the housing systems for dairy cows are of the type “cubicle housing system with slatted floor (1.2 m channel) according to Hanne Damgaard Poulsen (October 2008, personal communication). This is supported by Nielsen et al. (2008b).
- The slurry is pumped from the pre-tank in connection with the housing system to the outdoor storage.

⁵ JB3 has a clay content of 5 – 10 %, a silt content < 25 % and a fine sand content <40 %. JB6 has a clay content of 10 – 15 %, a silt content < 30 % and a fine sand content of 40 – 90 %

⁶ In Danish: Sengestald med spaltegulv (1.2 m kanal)

- As for pig slurry, it is assumed that the cattle slurry is stored outdoor in concrete slurry tanks. When storing cattle slurry, *a natural floating layer* will normally be created by the straw from the housing system, and this is regarded as a sufficient cover (Rasmussen et al., 2001 and Christiansen et al., 2003). Accordingly, the reference scenario for dairy cow slurry is based on the assumption that cut straw is *not* added to the slurry tank during storage.
- The transport distance from storage to application to fields is estimated to 10 km as for pig slurry. Sensitivity analysis is made for 2 km and 32 km.
- Cattle slurry is *applied with trail hose tankers* to the field, as for pig slurry, with a farm average of 140 kg N ha⁻¹ y⁻¹. This is the main application method (Personal communication with Birkmose (2008) and Pedersen (2008)). Part of the cattle slurry is also applied by injection, however, this technology is not included.
- According to Birkmose (2008), cattle are primarily raised on sandy soils in Denmark. This is supported by Halberg and Nielsen (2003), who state that in 1999, 15% of the total milk production came from conventional dairy farms on clay soils, whereas 71% of the milk production came from conventional dairy farms on sandy soils (The remaining 14-15% of the milk production came from farms with mixed production and the milk production was less than 10% of the farm income). However, it has been decided to establish the reference scenarios for both sandy soils and clay soils for cattle slurry.
- According to statistics from Nehmdahl (2009) on the distribution of crop types for pig and cattle farms, the most common crop type for cattle farms is grass (20.6%), closely followed by spring barley (17.2%), and maize (15.3%) (data from 2007). In order to make a reasonable realistic, though simplified, crop rotation for cattle farms, a five year rotation was utilised, with slurry N (kg ha⁻¹ y⁻¹) applied 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). As for pig slurry, it is assumed that the slurry is applied by trailing hoses during spring. For cattle slurry it is assumed that it is applied to all crops.

3.2 Composition of reference slurry

The chemical composition and other characteristics of the slurry in the reference scenarios are needed, as this is the *very basis* for the comparison between the “traditional slurry management” in the reference scenario with the new technologies in alternative scenarios. A comparison based on different slurry types or different slurry characteristics (e.g. different content of total-N) would give unreliable results, as the emissions of e.g. NH₃ are very dependent on the slurry content of N.

Furthermore, the chemical composition of the slurry is needed, as some of the environmental impacts are calculated relatively to the composition of the

slurry. For example, the ammonia emissions during storage are calculated as a percentage of the ammonium content in the slurry, the methane emissions are related to the organic matter and the fertiliser value is calculated in relation to the content of N, K and P in the slurry.

However, to define a fair “reference slurry composition” has not been easy, and to relate all the new slurry management technologies to this “theoretical reference slurry composition” is even more complicated. The composition of slurry excreted from the animal depends on the type of animal, diet, the age of the animal etc. The composition of the slurry after the housing system depends to a high degree on the housing system, management, storage time etc. Even slurry from the same farm might have different slurry composition from month to month due to non-controllable factors, e.g. temperature (time of the year) and the microbial decomposition by various micro organisms.

The alternative technologies have to be related to this “reference slurry composition” as far as possible. This is not an easy task, as the environmental data for some of these technologies (e.g. energy consumption, emissions and output products) is based on measurements on slurries with compositions that might be rather different than the “reference slurry composition” defined below. However, as described above, it would give even more unrealistic results to use different slurry compositions for each technology.

The slurry composition in this report is based on the “available data”, rather than a measure of “Danish average values”, which would have been ideal. Within each category, there are huge variations between minimum values and maximum values. The significance of some of these variations is discussed in the section “Sensitivity analysis”.

Preferably, the chemical composition of the slurry should be described in details. However, it has been difficult to find all the required data. In the reference scenario, the composition of the slurry is described by the following parameters. The parameters include:

- Dry matter (DM)⁷. DM is the fraction of the manure that is left after water has been evaporated due to heating at 80°C to constant weight or typically 24 hours. It typically constitutes 1 – 10% of the mass (Sommer et al., 2008).
- Ash. Ash is the remains after heating the DM at 550°C for one hour. Typically 20% of DM is ash.
- Volatile solids (VS)⁸. VS is the fraction of DM that volatilize when heating the DM at 550°C for one hour. This is the fraction lost during incineration. (Sommer et al., 2008). The volatile solids content is equal to the difference between the dry matter and ash ($VS = DM - \text{ash}$). Typically 80% of DM is VS.
- Total-N.
- Total-P
- Potassium (K)
- Carbon (C) (TOC – Total Organic Carbon).
- Copper (Cu)
- Zink (Zn)
- Density
- pH

⁷ In Danish: Tørstof (TS).

⁸ In Danish: Askefrit tørstof eller glødetab.

In the alternative scenarios, it has not been possible to obtain data for all the parameters and some of them have either been based on rough estimates or they have been left out.

It was the intention to include and follow the slurry content of ammonium (NH_4^+) or TAN” (total available Nitrogen i.e. $\text{NH}_4^+ + \text{NH}_3$) from the slurry was excretion until its application of the slurry to the field. Poulsen et al. (2001, page 130) and DJF (2008b) estimate that NH_4^+ -N content in pig slurry is approximately 75% of total-N and approximately 60% for cattle slurry, however, this is not used in their calculations (personal communication, H Damgaard Poulsen, January 2008). The estimate by Poulsen et al. (2001) is the content in the outdoor storage tank. Hansen et al. (2008) carried out measurements on more than 500 slurry samples coming from slurry after storage right before its application to the field. They measured a content of NH_4^+ -N corresponding to 79% of the total N in the slurry “ex storage” for fattening pigs and as 58% of the total N for dairy cows. However, it is not reasonable to assume that these NH_4^+ contents in the slurry after storage can be used as estimates for the NH_4^+ content in the slurry right after excretion and the same applies as regarding the slurry in the slurry pits in the housing units. This is because the content of NH_4^+ and/or TAN is, to a great degree, affected by biological processes, including nitrification (transformation of NH_4^+ to NO_3^-), denitrification (transformation of NO_3^- to N_2), mineralization (transformation of organic N to NH_4^+) or immobilization (the opposite of mineralization). These biological processes depend on a range of factors, e.g. the temperature and the C:N ratio of the slurry, and it has not been possible to establish reliable balances for NH_4^+ nor TAN. Accordingly, it has not been possible to include the content of NH_4^+ nor TAN in the slurry composition.

Due to lack of data, it has only been possible to include data on volatile solids (VS) in the reference scenario and not in the scenarios for the technologies for slurry management.

Originally, it was the intention to include sulphur (S) and emissions of hydrogen sulphide (H_2S). However, it was difficult to obtain data on hydrogen sulphide emissions for a majority of the processes. The budget of the project limited the amount of effort that could be allocated to an extensive search for data and accordingly hydrogen sulphide emissions have not been included and mass balances on sulphur could not be established. The additional amount of sulphur provided by the acidification technology is included for the acidification scenario, as it has special relevance for this specific scenario.

Data on the content of magnesium, calcium and sodium has not been collected, as they are regarded as insignificant for the overall environmental results of the life cycle assessment.

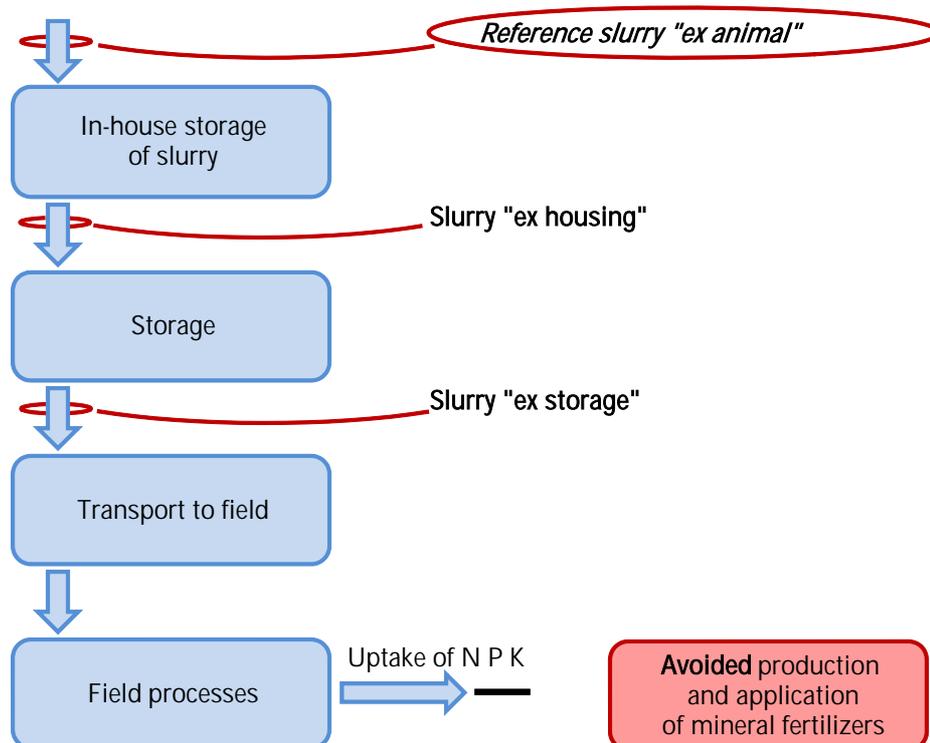
The composition of the slurry in the housing units is based on the Danish Normative system for assessing manure composition (Poulsen et al. (2001) and DJF (2008a)). Poulsen et al. (2001) established the technical background report, and the yearly updated values are published by Danmarks Jordbrugs Forskning (DJF). These data are combined with data from the literature.

The “reference slurry” is defined “ex animal”, i.e. right after the animals have excreted the slurry components. This is chosen as the reference point as this is where the system boundaries start, as described above. 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 pretank
- Slurry “ex storage”, i.e. after months of covered outdoor storage, measured right before application to field.

See figure 3.2.

Figure 3.2.
The reference slurry defined “ex housing”.



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. The “ex storage” values are lower than the “ex housing” values due to the dilution with rain water during the outdoor storage and due to degradation. The number of digits should not be seen as a measure of the precision, but is only included as the values are the foundation for further calculations. The data for dry matter (DM), nitrogen (N), phosphorus (P) and potassium (K) are based on the Danish Normative system for assessing manure composition (Poulsen et al. (2001), DJF (2008a) and DJF (2008b)). The rest of the data is based on various references, see Annex A.

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".

	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
<i>Total-N (DJF, 2008)</i>	<i>6.60 kg</i>	<i>5.54 kg</i>	<i>5.00 kg</i>
Total-N in this study	6.60 kg	5.48 kg	4.80 kg
NH ₄ ⁺ -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".

	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
- heavy degradable	54.2 kg	54.2 kg	51.9 kg
<i>Total-N (DJF, 2008)</i>	<i>6.87 kg</i>	<i>6.41 kg</i>	<i>6.02 kg</i>
Total-N in this study	6.87 kg	6.34 kg	5.79 kg
NH ₄ ⁺ -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 kg	12.1 kg	11.6 g
Zinc (Zn)	23.4 kg	23.4 kg	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 scenario

Data for the reference scenario is to a high degree based on two main references: Data from the Danish Normative system for assessing manure composition (Poulsen et al. (2001), DJF (2008a) and DJF (2008b)) and IPCC (2006). These data should be regarded as rather "static and rough estimates". These data have been used as these are widely used (e.g. for

national and international statistics for Green House Gas calculations and for the yearly publications from Plantedirektoratet containing the requirements for the farmers' fertiliser accounts according to Danish Law (Plantedirektoratet, 2008). Furthermore, the budget for this study could not include sophisticated modelling of the emissions. However, it has not been without problems using the Danish Normative system for assessing manure composition in combination with the data from IPCC (2006). First of all, the two references are not in accordance regarding mass balances – the loss of C due to CH₄ emissions in IPCC (2006) is not in accordance with the DM loss estimated by DJF (2008b). Secondly, the data are rather “static”. The Danish Normative system do not specify the retention time in the housing units, the pre-tank or the outdoor storage. Furthermore, there is no specification of the emissions from the pre-tank (accordingly, these are included in the data for outdoor storage in this study).

The main problem using data from IPCC (2006) is that the data are very “generic and static”. As example could be mentioned the N₂O emission from application of slurry to field, which is 1% of the N applied – regardless of soil type and local conditions (see Annex A). The IPCC estimate for N₂O is used for the Green House Gas calculations worldwide, and special Danish conditions are not taken into account. Another problem that could be mentioned is the in-house CH₄ emissions. In IPCC (2006), the emission factors (in kg CH₄ per kg VS) is 5.67 times higher for “storage > 1 month” than for “storage < 1 month” which is an unrealistic jump. The emission of CH₄ should rather have been modelled as a function of time. The CH₄ emissions depend on a range of factors, among these the retention time in the housing units, temperature and on the biological activity. As the CH₄ emissions for the slurry management technologies are calculated relative to the CH₄ emissions in this reference scenario, the significance of the uncertainty is reduced slightly for the comparisons to the new technologies.

3.4 Results of the Impact Assessment

3.4.1 Overall results of the impact assessment for the reference scenarios

The relative contributions to the environmental impact categories and resource consumptions for the reference scenario for pig slurry are shown in figure 3.3 and for dairy cow slurry in figure 3.4.

The contributions to each impact category are explained in the following sections.

The positive values (to the right) are the contributions to the environmental impacts and resource consumptions by the management of the pig slurry and dairy cow slurry.

The negative values (to the left) are “avoided environmental impacts”, because the nutrient content of pig and dairy cow slurry replace mineral fertilisers (if slurry was not applied to the field, the farmer would apply mineral fertilisers to the field instead). When the fertilisers are replaced, the production and application of these are avoided, and accordingly the system obtains a “deduction” when the mineral fertilisers are subtracted from the system.

The numbering of processes (“A2” and “A3” refers to the number of the section in Annex A, where the processes are described).

Figure 3.3.

environmental impacts and resource consumption from the reference scenario for pig slurry. soil type “JB3” and “JB6”. 10 and 100 years time horizon for global warming and for aquatic eutrophication (N).

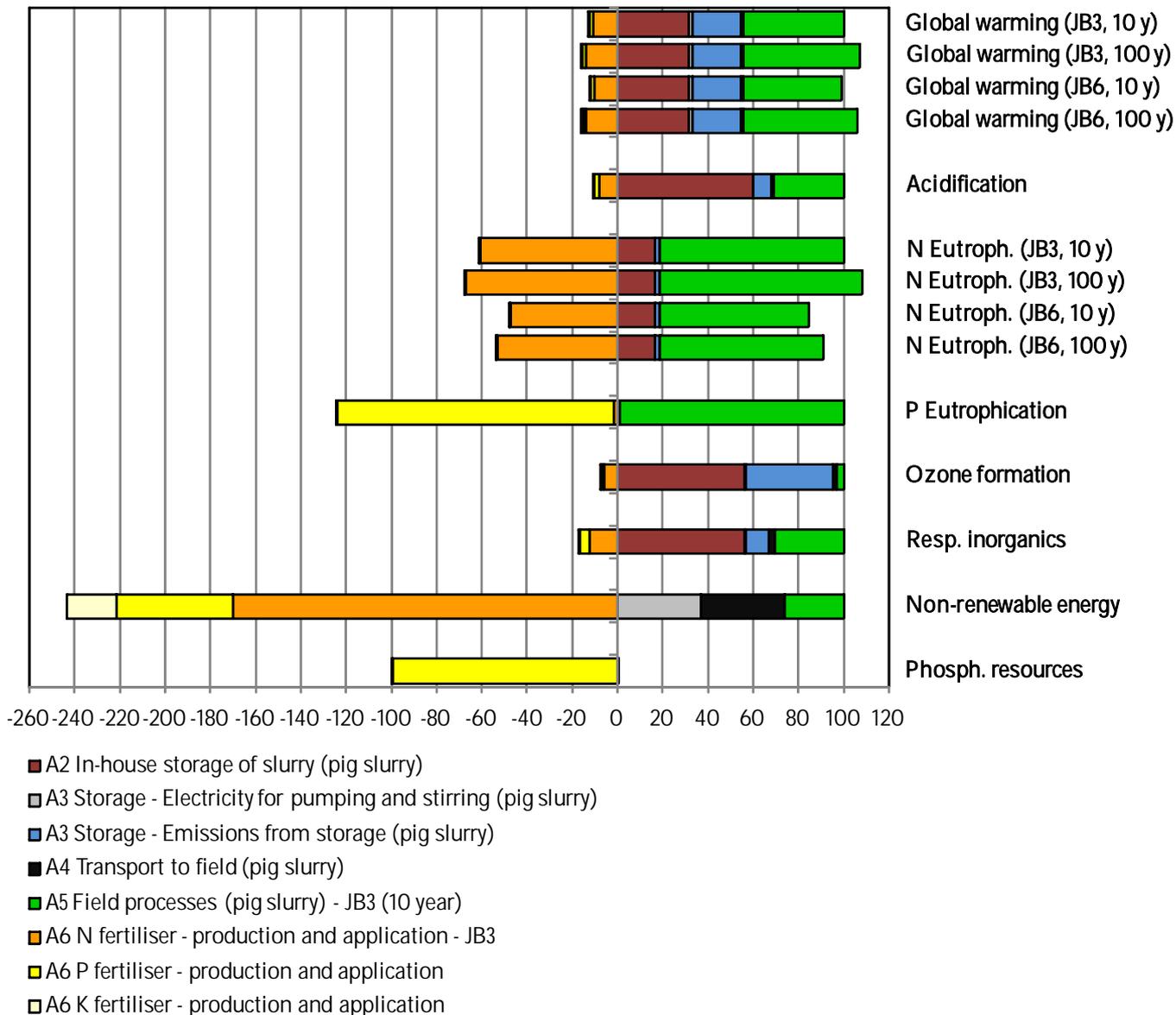
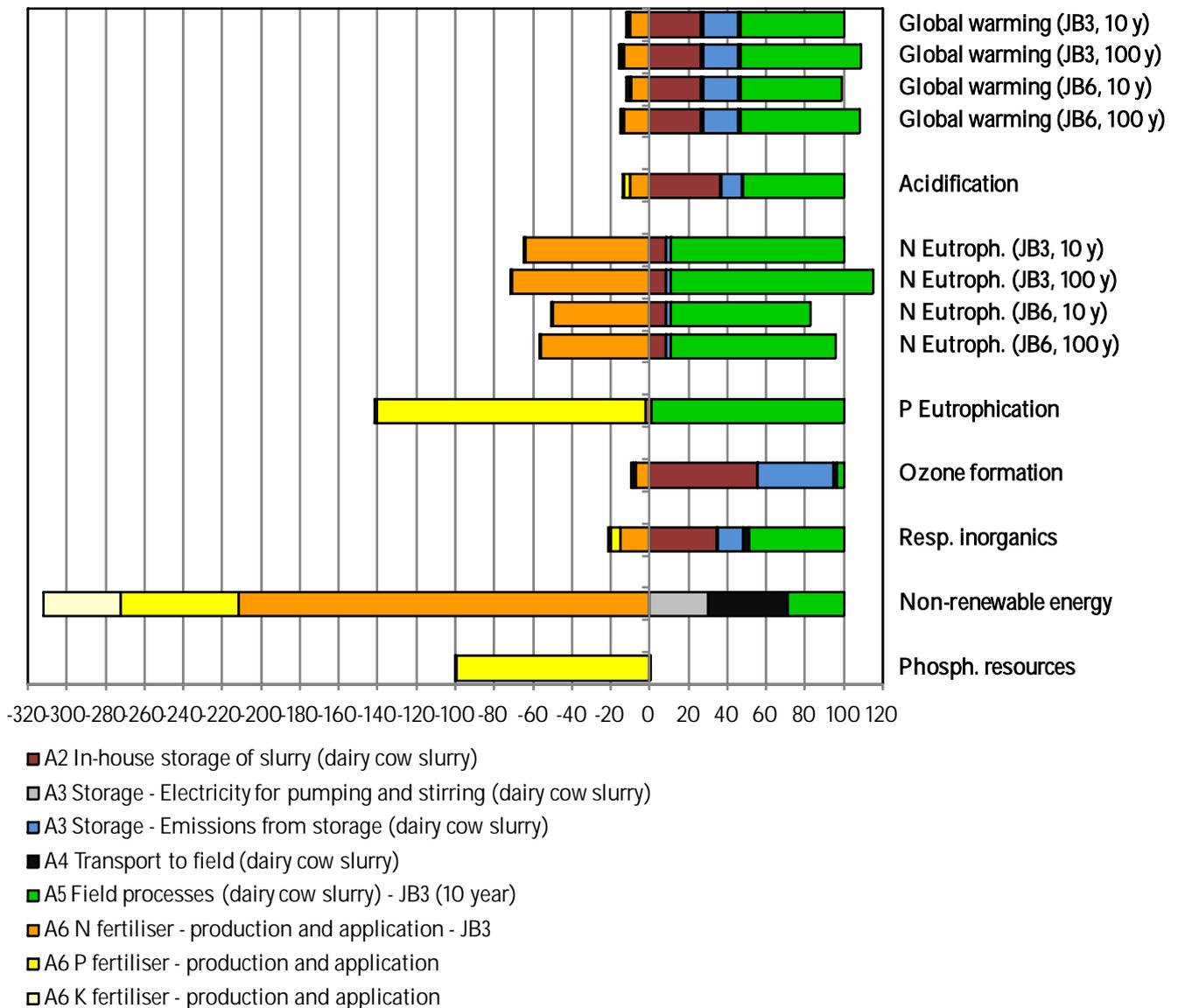


Figure 3.4. environmental impacts and resource consumption from the reference scenario for dairy cow slurry, soil type "JB3" and "JB6". 10 and 100 years time horizon for global warming and for aquatic eutrophication (N).



3.4.2 Normalised results

In figure 3.5, the "normalised" environmental impacts for pig slurry and dairy cow slurry are shown. The environmental impacts are normalised by use of the EDIP method, i.e. dividing the contributions from the slurry by the yearly average contribution from a person. The unit for the normalised impacts are "Person Equivalents", and the normalised impacts can be interpreted as "a percent of the average yearly contribution by a person". As can be seen at figure 3.5, the contribution from 1000 kg pig slurry contributes to the global warming by approximately 3.3 % of one person's yearly contribution to the global warming.

It has not been possible to normalise the contributions to "respiratory inorganics", as the factors for these are based on the IMPACT 2002+ method, as explained in section 2.7.

The category “Non-renewable energy” is also based on the IMPACT 2002+ method. The IMPACT 2002+ method includes a normalisation factor for this category, based on the average energy consumption by an “average European”. The exact value should be taken with care, as it is not part of the EDIP method used for the normalisation of all the other categories. However, it provides an indication of the magnitude.

The normalisation factor for phosphorus is based on Nielsen and Wenzel (2005), who calculated that the average usage of phosphate rock is in the order of 22 kg per world citizen per year. There is significant uncertainty on this figure. However, it provides an indication of the magnitude.

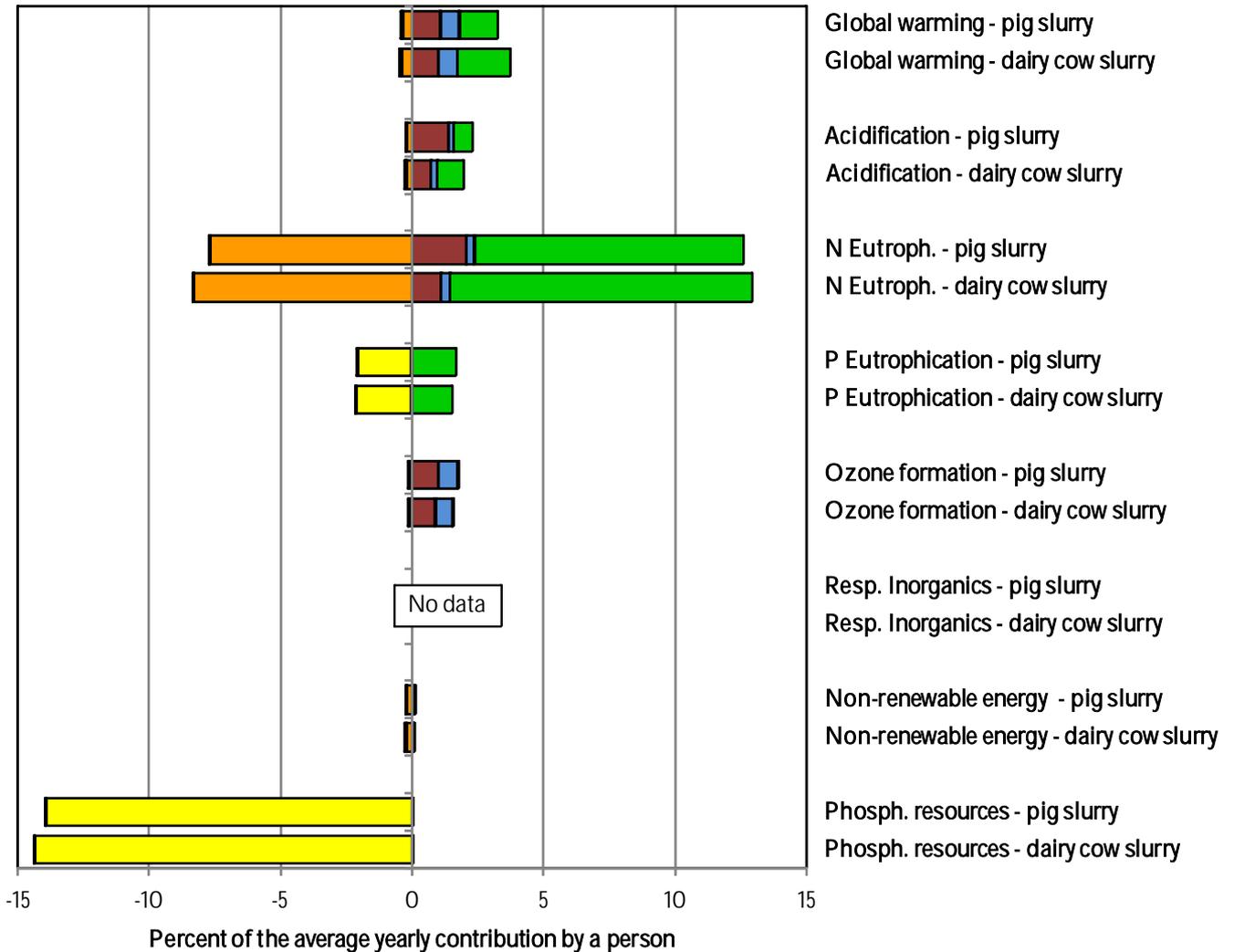
When interpreting the normalised results, it should be kept in mind, that normalised results are not a measure of the relative *importance* of the environmental impacts. However, the normalised results are very close to the weighted results by the EDIP method, as the weighting factors are all in the range of 1.1-1.4 (except for ozone layer depletion, which is not included in this study).

From the normalised data in figure 3.5, it can be seen that:

- Slurry management has a relatively large contribution to “Aquatic eutrophication (nitrogen compounds)” compared to the other impact categories. The contribution by the slurry is partly counterbalanced by the avoided contribution from the replaced mineral N fertilisers, and when regarding “net contributions” (contribution minus avoided), the contribution to aquatic eutrophication (N) is at the same magnitude as most of the other environmental impacts.
- The contribution to “Aquatic eutrophication (phosphorus)” is also relatively large. However, this is counterbalanced by the avoided contributions from mineral P fertilisers.
- The phosphorous resources, which is saved due to the use of slurry at the field replacing mineral P fertiliser is relatively large.
- The normalised consumption of non-renewable energy is relatively small compared to the other categories. It means that the energy consumption of the systems is not a “big issue”.

Figure 3.5.

Normalised contributions to environmental impacts from the reference scenario for pig slurry and dairy cow slurry, soil type "JB3" and 10 years time horizon for global warming and for aquatic eutrophication (N).



3.4.3 Global warming

For pig slurry as well as dairy cow slurry, the main contributions to global warming come from the emissions from the field processes, the outdoor storage of slurry and the emissions from the indoor storage of slurry, see figure 3.3 and 3.4. The contributions from the indoor storage and the outdoor storage are totally dominated by contributions from CH_4 . The contributions from the field are caused by CO_2 and N_2O emissions.

The “negative contributions” to the global warming (to the left in figure 3.3 and 3.4) is due to the avoided fertilisers (predominantly due to the avoided N mineral fertiliser). As described in Annex A, the slurry contains N, P and K nutrients, which replace application and production of mineral fertilisers. As the application of mineral N fertiliser leads to N_2O emissions from the soil, and as the production of N mineral fertiliser leads to N_2O emission during the production of nitric acid from ammonia, these are avoided. The application of slurry also leads to N_2O emission. However, due to the huge uncertainty on the N_2O emission factors from both slurry and mineral N fertiliser, it is not possible to clearly express whether the application of slurry leads to a net reduction of the total N_2O emission or opposite. In this study, the same N_2O emission factor has been used for the field emissions of N_2O from slurry and from mineral N fertilisers per kg N.

In table 3.3 the contributions to Global Warming from management of pig slurry in the reference scenario is shown. The contributions from dairy cow slurry are shown in table 3.4. The % should be taken with care due to the high uncertainties – it is only a very rough estimate!

Table 3.3.

Contributions to global warming from pig slurry in the reference scenario.

Per 1000 kg of slurry "ex animal". The % should be taken with care due to the high uncertainties – it is rather rough estimates! The number of digits is *not* an expression of the uncertainty.

Contributions to Global warming	kg CO ₂ eq	Uncertainty Range kg CO ₂ eq.	% of total positive contribution	Comments and reference on uncertainty
CH₄				
CH ₄ from in-house storage	75.7	[7 – 150]	25.3%	Based on IPCC (2006). If IPCC data for < 1 month storage had been chosen, the emissions would be a factor 5.67 times lower. In addition, an uncertainty on a factor 2 is assumed as on the other data from IPCC (2006), see below.
CH ₄ from "Storage" (in pre-tank and outdoor storage)	44.6	[15 – 134]	14.9%	Data based on IPCC (2006). IPCC (2006) does not estimate the uncertainty. The uncertainty must be high – the emissions depend on storage time which is not included in the IPCC model. Estimated uncertainty: A factor 3.
N₂O				
N ₂ O from in-house storage	11.2	[5.6 – 22]	3.7%	IPCC (2006) estimates that the uncertainty for this is a factor 2.
N ₂ O from storage (pre-tank and outdoor storage)	16.0	[8 – 32]	5.3%	IPCC (2006) estimates that the uncertainty for this is a factor 2.
N ₂ O from field	34.9	[12 – 105]	11.7%	IPCC (2006) estimates that the uncertainty for this is a factor 3.
Avoided N ₂ O due to avoided production of mineral fertilisers and application of these to field	-32.0	[- 11 – - 96]	-10.7%	IPCC (2006) estimates that the uncertainty for this is a factor 3. The uncertainties on the N ₂ O emission from production of mineral N fertiliser in the SimaPro database is at the same magnitude (see Annex A).
CO₂				
CO ₂ from electricity for pumping and stirring	3.6	[1.8 – 7.3]	1.2%	Estimate: A factor 2 (mainly on the electricity consumption by the gear)
CO ₂ from transport	3.1	[1.5 - 6]	1.0%	Estimate: A factor 2.
Avoided CO ₂ due to avoided production of mineral fertilisers	-17.5	[-9- -26]	-5.9%	Change if other marginal N and P fertiliser was chosen, see Annex A. Sensitivity analysis in SimaPro.
CO ₂ from field processes from avoided mineral N fertiliser ¹ (biogenic CO ₂)	14.3	[9- 20]	4.8%	Estimate of the uncertainty: ± 40%
CO ₂ from field processes (during 10 years) (biogenic CO ₂)	88.7	[53-124]	29.6%	Estimate of the uncertainty: ± 40%
Residue				
Residue from other processes	5.6	Not estimated	1.9%	
TOTALS				
Total POSITIVE contributions	299.3	[150-600]	100%	Rough estimate: A factor 2
Total AVOIDED contributions	-51.2	[-25--100]	-17.1%	Rough estimate: A factor 2
Total NET contribution (= positive - negative)	248.0	[125-500]	82.9%	Rough estimate: A factor 2

¹ As explained in table A.18 in Annex A, application of mineral N fertiliser gives rise to extra soils C storage during the 10 years time horizon due to more residues from a larger crop (C-tool). This means that application of extra mineral N fertiliser saves emissions of CO₂, and opposite: Application of less mineral N fertiliser means that extra C is not stored in the soil, accordingly it corresponds to a positive contribution to global warming.

Table 3.4.

Contributions to global warming from dairy cow slurry in the reference scenario. Per 1000 kg of slurry "ex animal". The % should be taken with care due to the high uncertainties – it is rather rough estimates! The number of digits is *not* an expression of the uncertainty.

Contributions to Global warming	kg CO ₂ eq	Uncertainty Range kg CO ₂ eq.	% of total positive contribution	Comments and reference on uncertainty
CH₄				
CH ₄ from in-house storage	65.6	[6 – 131]	19.2%	Based on IPCC (2006). If IPCC data for < 1 month storage had been chosen, the emissions would be a factor 5.67 times lower. In addition, an uncertainty on a factor 2 is assumed as on the other data from IPCC (2006), see below.
CH ₄ from "Storage" (in pre-tank and outdoor storage)	38.6	[13 – 116]	11.3%	Data based on IPCC (2006). IPCC (2006) does not estimate the uncertainty. The uncertainty must be high – the emissions depend on storage time which is not included in the IPCC model. Estimated uncertainty: A factor 3.
N₂O				
N ₂ O from in-house storage	9.3	[4.7 – 19]	2.7%	IPCC (2006) estimates that the uncertainty for this is a factor 2.
N ₂ O from storage (pre-tank and outdoor storage)	16.6	[8 – 33]	4.8%	IPCC (2006) estimates that the uncertainty for this is a factor 2.
N ₂ O from field	39.8	[13 – 119]	11.6%	IPCC (2006) estimates that the uncertainty for this is a factor 3.
Avoided N ₂ O due to avoided production of mineral fertilisers and application of these to field	-34.7	[-12 – - 104]	-10.1%	IPCC (2006) estimates that the uncertainty for this is a factor 3. The uncertainties on the N ₂ O emission from production of mineral N fertiliser in the SimaPro database is at the same magnitude (see Annex A).
CO₂				
CO ₂ from electricity for pumping and stirring	2.6	[1.3 – 5.2]	0.8%	Estimate: A factor 2 (mainly on the electricity consumption by the gear)
CO ₂ from transport	2.9	[1.5 - 6]	0.9%	Estimate: A factor 2.
Avoided CO ₂ due to avoided production of mineral fertilisers	-19.5	[-10- -30]	-5.7%	Change if other marginal N and P fertiliser was chosen, see Annex A. Sensitivity analysis in SimaPro.
CO ₂ from field processes from avoided mineral N fertiliser ¹ (biogenic CO ₂)	15.5	[9- 22]	4.5%	Estimate of the uncertainty: ± 40%
CO ₂ from field processes (during 10 years) (biogenic CO ₂)	132	[79-185]	38.6%	Estimate of the uncertainty: ± 40%
Residue				
Residue from other processes	17.3	Not estimated	5.1%	
TOTALS				
Total POSITIVE contributions	342.1	[170-685]	100%	Rough estimate: A factor 2
Total AVOIDED contributions	-56.0	[-28-112]	-16.4%	Rough estimate: A factor 2
Total NET contribution (= positive - negative)	286.1	[140-570]	83.6%	Rough estimate: A factor 2

¹ As explained in table A.18 in Annex A, application of mineral N fertiliser gives rise to extra soils C storage during the 10 years time horizon due to more residues from a larger crop (C-tool). This means that application of extra mineral N fertiliser saves emissions of CO₂, and opposite: Application of less mineral N fertiliser means that extra C is not stored in the soil, accordingly it corresponds to a positive contribution to global warming.

In order to assess the significance of some of the assumptions made, and as some of the data used for this Life Cycle Assessment has a high uncertainty, sensitivity analysis has been carried out for a variety of parameters:

From table 3.3 and table 3.4 it can be seen that:

- When taking the uncertainties into consideration, there is no statistical difference between the contributions from pig slurry and dairy cow slurry, except for the field processes.
- The main contributions come from CH₄ in the housing units, CH₄ during storage, N₂O from field processes and biogenic CO₂ from field processes.
- The emissions of CH₄ are generally found to have a very high uncertainty, as described in Annex A. They are based on rough estimates rather than “well founded scientific research”. A critical point to mention is the calculation of the CH₄ emissions from indoor storage. As mentioned in Annex A, the uncertainty on the CH₄ emissions from the housing units is high. The emission factors (in kg CH₄ per kg VS) is 5.67 times higher for “storage > 1 month” than for “storage < 1 month” which is an unrealistic jump. The emission of CH₄ should rather have been modelled as a function of time. In this study, the high emission factor from IPCC (2006) has been used as a conservative estimate. It has not been possible to improve the estimates - the area needs more scientific research.
- The CO₂ emissions from the housing units and the outdoor storage are based on mass balances, based on the rough estimate of DM loss in the Danish Norm data (Poulsen et al., 2001) and DJF (2008). However, as the CH₄ emissions have a global warming potential that is 23 times higher than CO₂, the uncertainties of CH₄ are more important.
- The CO₂ emissions from the field have a relatively high contribution to global warming (approximately at the same level as the CH₄ emissions from the housing units). Hence these are also important. The CO₂ emissions from the field are modelled by the use of C-TOOL. The CO₂ emissions are very dependent on the time horizon. In this study the calculation is based on a 10 years perspective, but if using a 100 years perspective, the CO₂ emissions will be 22% higher for both pig slurry and dairy cow slurry.
- The N₂O emissions from fields are very important, and the factors are very uncertain. The N₂O emissions depend to a great extent on the soil conditions and could be modelled in advanced models. However, this has not been possible within the budget and frames of this study. The direct N₂O emissions are based on IPCC (2006, table 11.1).
- Sensitivity analysis on the transport shows that transport of slurry from the outdoor storage tank to the fields has no significance for the overall contributions to global warming.

- Furthermore, the electricity consumption for pumping and stirring is relatively unimportant for the overall contributions to global warming from slurry. Accordingly, a sensitivity analysis on the marginal electricity production will not change the results.
- The choice of marginal N and P fertiliser also influences the results – the “avoided contribution” to global warming. However, the uncertainty on the N₂O emissions from field dominates the overall uncertainty for the avoided contribution from mineral fertilisers.
- The difference between soil types JB3 and soil type JB6 is very small and it has no significance for the overall contributions to global warming (see figure 3.3. and 3.4).
- After a period of 100 years, the CO₂ emissions from the applied slurry to the soil are higher than after a period of 10 years, which is visible at figure 3.3 and 3.4. The increase is only partly counterbalanced by the differences in CO₂ emissions from the replaced mineral N fertiliser. As explained in table A.18 in Annex A, application of mineral N fertiliser gives rise to extra storage of C in the soil during the 10 years time horizon due to more residues from a larger crop. This means that application of extra mineral N fertiliser reduces the emissions of CO₂, and opposite: Application of less mineral N fertiliser means that less C is stored in the soil, accordingly it corresponds to a positive net contribution to global warming. The positive CO₂ contribution is higher on a 100 year horizon than on a 10 year horizon.

The incorporation of C in soil for the reference scenario is shown in table 4.1 and 4.2 in the end of section 4. For pig slurry, a net amount of 3.6 kg of C (per 1000 kg pig slurry “ex animal”) is still remaining in the soil after a period of 10 years, corresponding to 13.2 kg CO₂. After 100 years, the net amount of C remaining in the soil is in the magnitude of 1 kg C, corresponding to 3.8 kg CO₂. For dairy cow slurry, the net amount of stored C in the soil is approximately 7 kg after 10 years, and 2 kg C after 100 years.

According to the uncertainty on the data, the relative contributions from CH₄ emissions from the housing units, CH₄ emissions from the outdoor storage and the CO₂ and N₂O emissions from the fields could be different than shown in figure 3.3 (for pig slurry) and figure 3.4 (for dairy cow slurry). However, in spite of these uncertainties, there is no doubt, that these are the important emissions contribution to the global warming for both pig slurry and dairy cow slurry.

3.4.4 Acidification

The main contributions to acidification come from the in-house storage of slurry. Furthermore, significant contributions come from the field processes and the outdoor storage also contributes some. As can be seen when comparing figure 3.3 and 3.4, the relative contribution from the housing units is higher for pig slurry than for dairy cow slurry.

As can be seen from table 3.5 and 3.6, the contribution to acidification is totally dominated by NH₃ emissions. The unit for the characterised results in table 3.5 are expressed as the area of ecosystem within the full deposition area

which is brought to exceed the critical load of acidification as a consequence of the emission (area of unprotected ecosystem, i.e. m² UES), as defined by the EDIP 2003 method (Hauschild et al, 2005).

Table 3.5.

Contributions to acidification from pig slurry in the reference scenario.

Per 1000 kg of slurry "ex animal". The % should be taken with care due to the high uncertainties – it is rather rough estimates! The number of digits is *not* an expression of the uncertainty.

Contributions to Acidification	m ² UES	Uncertainty Range m ² UES	% of total positive contribution	Comments and reference on uncertainty
NH₃				
NH ₃ from in-house storage	29.8	[15 – 60]	59.2%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NH ₃ from "Storage" (in pre-tank and outdoor storage)	3.1	[1.5 – 6]	6.1%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NH ₃ from field	15.3	[7.6 – 31]	30.4%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Avoided NH ₃ from avoided mineral fertilisers	-2.9	[-1.4 – -6]	-5.7%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NO_x				
NO _x from slurry (in-house, storage, and field)	1.6	[0.8 – 3]	3.3%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NO _x from electricity for pumping and stirring	0.03	[0.02-0.07]	0.1%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NO _x from transport	0.2	[0.1-0.4]	0.4%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NO _x from avoided production of fertilisers	-0.9	[-0.43- - 1.7]	-1.7%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
SO₂				
SO ₂ from transport	0.1	[0.05 –0.2]	0.2%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Avoided SO ₂ due to avoided production of mineral fertilisers	-1.7	[-0.8- -3.4]	-3.3%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Residue				
Residue from other processes	0.1	Not estimated	0.2%	
TOTALS				
Total POSITIVE contributions	50.3	[25-100]	100%	Rough estimate: A factor 2
Total AVOIDED contributions	-5.5	[-2.7--11]	-10.6%	Rough estimate: A factor 2
Total NET contribution (= positive - negative)	44.8	[22-90]	89.1%	Rough estimate: A factor 2

Table 3.6.

Contributions to acidification from dairy cow slurry in the reference scenario. Per 1000 kg of slurry "ex animal". The % should be taken with care due to the high uncertainties – it is rather rough estimates! The number of digits is *not* an expression of the uncertainty.

Contributions to Acidification	m ² UES	Uncertainty Range m ² UES	% of total positive contribution	Comments and reference on uncertainty
NH₃				
NH ₃ from in-house storage	15.4	[8 – 31]	35.7%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NH ₃ from "Storage" (in pre-tank and outdoor storage)	3.7	[2 – 7]	8.4%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NH ₃ from field	22	[11 – 44]	50.9%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Avoided NH ₃ from avoided mineral fertilisers	-3.1	[-1.6 – -6]	-7.2%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NO_x				
NO _x from slurry (in-house, storage, and field)	1.7	[0.9 – 3.4]	3.9%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NO _x from electricity for pumping and stirring	0.02	[0.01-0.05]	0.1%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NO _x from transport	0.2	[0.1-0.4]	0.4%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NO _x from avoided production of fertilisers	-0.9	[-0.5- -1.9]	-2.2%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
SO₂				
SO ₂ from transport	0.1	[0.05 – 0.2]	0.2%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Avoided SO ₂ due to avoided production of mineral fertilisers	- 1.8	[-1- -4]	-4.1%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Residue				
Residue from other processes	0.05	Not estimated	0.1%	
TOTALS				
Total POSITIVE contributions	43.3	[22-87]	100%	Rough estimate: A factor 2
Total AVOIDED contributions	-5.9	[-3--12]	-13.7%	Rough estimate: A factor 2
Total NET contribution (= positive - negative)	37.3	[19-75]	86.3%	Rough estimate: A factor 2

As can be seen from table 3.5 and 3.6, less than 4% of the contributions to acidification come from nitrogen oxides, and less than 0.5% from electricity production and transport. The avoided production of mineral fertilisers leads to a small amount of nitrogen oxides and sulphur dioxide emissions being avoided, however it corresponds to less than 6% of the total contribution to acidification. Again, the relative contributions of NH₃ from the in-house storage of slurry, the field processes and the outdoor storage are very dependent on the uncertainties on the data.

The NH₃ emissions are mainly based on the Danish Norm Data. The uncertainty on these data is not stated, and the ammonia emissions are very dependent on temperature, biological activity and slurry composition (e.g. pH), however, it is assumed that the NH₃ emissions used in this report is a rather good estimate for the "average Danish conditions".

The results of the Life Cycle assessment for the reference scenario show that:

- Even when acknowledging that there is uncertainty on the Danish Norm data for NH_3 emissions, it is likely that the contributions to acidification mainly come from in-house emissions of NH_3 , field emissions of NH_3 and outdoor storage NH_3 emissions. It is likely, that the relative contributions are as shown in figure 3.3 for pig slurry and 3.4 for dairy cow slurry.
- Transport of slurry from outdoor storage to field is unimportant for the overall contributions to acidification.
- The electricity consumption for pumping and stirring is relatively unimportant for the overall contributions to acidification.

3.4.5 Aquatic eutrophication (N)

In table 3.7 and 3.8 the contributions to aquatic N-eutrophication are shown in N-equivalents. The EDIP 2003 method includes modelling of the fate of the substances, and the EDIP 2003 impact potential thus represents the fraction of the emission which can actually be expected to reach different aquatic systems (Hauschild et al., 2005) (i.e. not all of 1 kg N leached actually reach aquatic systems). The contributions to aquatic eutrophication (N) are dominated by nitrogen leaching from the field. NH_3 emissions from the slurry also contribute to some extent (contributions from the indoor storage is due to NH_3 emissions in figure 3.3. and 3.4). The application of slurry leads to nitrogen leaching, however, this is partly counterbalanced by the avoided N leaching due to the replaced amount of mineral N fertiliser.

As can be seen from figure 3.3 and 3.4, the N leaching from the slurry is significantly lower from soil type JB6 than from soil type JB3. However, as the N leaching from the mineral N fertiliser is also lower, the net leaching is within the same order of magnitude (only slightly lower for JB6, a maximum of 10% difference for the net contributions from the overall system).

As can be seen from figure 3.3 and 3.4, there are significant differences between the 10 years time horizon and the 100 years time horizon. The nitrogen leaching from the slurry is significant higher during the 100 years, however, this is to some extent counterbalanced because the avoided nitrogen leaching from the replaced mineral N fertiliser is also higher. In fact, the “net contribution” is less than 4% higher on a 100 year horizon than for the 10 year horizon (pig slurry, JB3 and JB6). For dairy cow slurry the difference is less than 3% for both soil type JB3 and JB6. The reason for the higher nitrogen leaching at the long time-scale is the mineralisation of organic matter, of which a substantial part goes to leaching.

Table 3.7.

Contributions to aquatic N-eutrophication from pig slurry in the reference scenario. Per 1000 kg of slurry "ex animal". The % should be taken with care due to the high uncertainties – it is rather rough estimates! The number of digits is *not* an expression of the uncertainty.

Contributions to Aquatic N-eutrophication	N-equivalents	Uncertainty Range N-eq.	% of total positive contribution	Comments and reference on uncertainty
NH₃				
NH ₃ from in-house storage	0.24	[0.12 – 0.48]	16.1%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NH ₃ from "Storage" (in pre-tank and outdoor storage)	0.025	[0.013 – 0.05]	1.7%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NH ₃ from field	0.13	[0.06 – 0.25]	8.2%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Avoided NH ₃ from avoided mineral fertilisers	-0.024	[-0.012 – -0.05]	-1.6%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
N leaching from field				
N leaching from fields (from slurry)	1.1	[0.6 – 2.2]	72.7%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 1.5.
Avoided N leaching from fields (due to avoided mineral N fertilisers)	-0.9	[-0.5- -1.8]	- 58.9%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 1.5.
NO_x				
NO _x total in system	0.011	[0.006-0.02]	0.7%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Residue				
Residue from other processes	Almost 0	Not estimated	<0.2%	
TOTALS				
Total POSITIVE contributions	1.51	[0.8-3.0]	100%	Rough estimate: A factor 2
Total AVOIDED contributions	-0.93	[-0.5- -1.9]	-61.3%	Rough estimate: A factor 2
Total NET contribution (= positive - negative)	0.59	[0.3 – 1.2]	38.7%	Rough estimate: A factor 2

Table 3.8.

Contributions to aquatic N-eutrophication from dairy cow slurry in the reference scenario. Per 1000 kg of slurry "ex animal". The % should be taken with care due to the high uncertainties – it is rather rough estimates! The number of digits is *not* an expression of the uncertainty.

Contributions to Aquatic N-eutrophication	N-equivalents	Uncertainty Range N-eq.	% of total positive contribution	Comments and reference on uncertainty
NH₃				
NH ₃ from in-house storage	0.13	[0.06 – 0.25]	8.1%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NH ₃ from "Storage" (in pre-tank and outdoor storage)	0.03	[0.015 – 0.06]	1.9%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NH ₃ from field	0.18	[0.09 – 0.36]	11.6%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Avoided NH ₃ from avoided mineral fertilisers	-0.025	[-0.013– -0.05]	-1.6%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
N leaching from field				
N leaching from fields (from slurry)	1.2	[0.6 – 2.4]	77.0%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Avoided N leaching from fields (due to avoided mineral N fertilisers)	-0.96	[-0.5- -1.9]	- 62.0%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 1.5.
NO_x				
NO _x total in system	0.01	[0.005-0.02]	0.7%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Residue				
Residue from other processes	Almost 0	Not estimated	<0.2%	
TOTALS				
Total POSITIVE contributions	1.55	[0.8-3.1]	100%	Rough estimate: A factor 2
Total AVOIDED contributions	-1.00	[-0.5- -2.0]	-64.5%	Rough estimate: A factor 2
Total NET contribution (= positive - negative)	0.55	[0.28 – 1.1]	35.5%	Rough estimate: A factor 2

3.4.6 Aquatic eutrophication (P)

The results for the aquatic phosphorous eutrophication (P) have a very high uncertainty due to lack of data and due to that it has not been possible to apply advanced modelling within the frames of the study. The results are mainly affected by two rough assumptions: The assumption that 0.6% of the applied phosphorus is leaching and reach the aquatic environment (both for animal slurry and for mineral fertilisers) and the assumptions related to the data for the leaching of P from production of mineral fertilisers (see Annex A, section A.5.6). Furthermore, there is significant uncertainty on the Life Cycle Inventory data for the production of mineral P fertiliser.

First of all, there is a high uncertainty on the fraction of phosphorus that is actually leaching. However, as it is assumed to be the same for P leaching from slurry and P leaching from the replaced mineral fertiliser, the uncertainty to some degree "outbalance" each other. The assumption that 0.6% of the P are leaching and reach the aquatic environment have a high uncertainty and depends to a high degree on the soil type and the content of phosphorus in the soil. Soils in areas with a high density of animals (pigs or cattle) generally have a higher content of P than soils in areas with a low density of animals. In

figure 3.3 and 3.4 it seems like that the amount of P leaching from the slurry is more than counterbalanced by the same amount of P leaching from the avoided mineral P fertiliser. However, this is only correct if the leaching from 1 kg P in slurry is identical to the leaching from 1 kg P in mineral fertilisers, which might not always be the case. The discussion of P leaching from slurry vs. mineral fertilisers is beyond the scope of this study.

As discussed in Annex A, sensitivity analysis has been carried out for different kind of mineral P fertilisers. Changing mineral P fertiliser might increase the P leaching by a factor 8.6, when calculating with phosphoric acid plants in Morocco dispose the phosphogypsum directly to the sea (as described in section A.6.4), which has huge significance for the overall conclusions.

In this study, the uncertainty related to phosphorous eutrophication to aquatic environment is rather insignificant, as all the alternative new technologies has the same contribution as the reference system. However, in future life cycle assessments based on this report, it is strongly recommended to perform sensitivity analysis as described in Annex A.

3.4.7 Photochemical Ozone Formation ("smog")

In the EDIP 2003 method, the photochemical ozone formation potentials (for human exposure) are expressed in the unit $\text{pers} \cdot \text{ppm} \cdot \text{hours}$. This corresponds to the accumulated exposure above the threshold of 60 ppb times the number of persons which are exposed as a consequence of the emission. No threshold critical for chronic exposure of humans to ozone has been established. Instead, the threshold of 60 ppb is chosen as the long-term environmental objective for the EU ozone strategy proposed by the World Health Organisation, WHO.

For vegetation, the impact is expressed as the accumulated exposure (duration times exceedance of threshold) above the threshold of 40 ppb times the area that is exposed as a consequence of the emission. The threshold of 40 ppb is chosen as an exposure level below which no or only small effects occur. The unit for vegetation exposure is $\text{m}^2 \cdot \text{ppm} \cdot \text{hours}$ (Hauschild et al., 2005).

In this study, only the human exposure is included, as the results calculated by SimaPro shows very similar patterns for the two impacts (same sources, same relative distributions etc).

As can be seen in table 3.10 and 3.11, the main contributor to photochemical ozone formation is the CH_4 emissions from the in-house storage of slurry and the outdoor storage of slurry. Furthermore, emissions of nitrogen oxide (from in-house and outdoor storage) also contribute to the ozone formation. The high uncertainty in the CH_4 emission is discussed above under global warming. Accordingly, conclusions on the relative contributions from respectively the in-house storage and the outdoor storage should be taken with care.

As can be seen in table 3.10 and 3.11, there are some contributions to photochemical ozone formation from NO_x from the slurry in the housing units, during storage and after application to field. The uncertainty on these emissions is very high, as the NO and NO_2 emissions are basically rough estimates rather than measurements. Accordingly, these values should be taken with care.

The contributions from electricity consumption and transport are not significant.

The choice of marginal N, P and K fertilisers are relatively unimportant for the overall contributions to the ozone formation.

Table 3.9.

Contributions to Photochemical Ozone Formation from pig slurry in the reference scenario. Per 1000 kg of slurry "ex animal". The % should be taken with care due to the high uncertainties – it is rather rough estimates! The number of digits is *not* an expression of the uncertainty.

Contributions to photochemical ozone formation	pers □ ppm □ hours	Uncertainty Range pers □ ppm □ hours	% of total positive contribution	Comments and reference on uncertainty
CH₄				
CH ₄ from in-house storage	0.095	[0.008 – 0.19]	53.3%	Based on IPCC (2006). If IPCC data for < 1 month storage had been chosen, the emissions would be a factor 5.67 times lower. In addition, an uncertainty on a factor 2 is assumed as on the other data from IPCC (2006), see below.
CH ₄ from "Storage" (in pre-tank and outdoor storage)	0.056	[0.02 – 0.17]	31.4%	Data based on IPCC (2006). IPCC (2006) does not estimate the uncertainty. The uncertainty must be high – the emissions depend on storage time which is not included in the IPCC model. Estimated uncertainty: A factor 3.
NO_x				
NO _x from slurry (in-house, storage, and field)	0.023	[0.008-0.068]	12.7%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 3 (the values in the study are very rough estimates).
NO _x from electricity for pumping and stirring	0.0005	[0.0002-0.001]	0.3%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NO _x from transport	0.003	[0.001-0.005]	1.5%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NO _x from avoided production of fertilisers	-0.012	[-0.006 – 0.024]	-6.6%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Residue				
Residue from other processes	Approx. 0	Not estimated	< 1%	
TOTALS				
Total POSITIVE contributions	0.179	[0.09-0.36]	100%	Rough estimate: A factor 2
Total AVOIDED contributions	-0.014	[-0.007-0.029]	-7.7%	Rough estimate: A factor 2
Total NET contribution (= positive - negative)	0.165	[0.08-0.33]	92.3%	Rough estimate: A factor 2

Table 3.10.

Contributions to Photochemical Ozone Formation from dairy cow slurry in the reference scenario. Per 1000 kg of slurry "ex animal". The % should be taken with care due to the high uncertainties – it is rather rough estimates! The number of digits is *not* an expression of the uncertainty.

Contributions to photochemical ozone formation	pers □ ppm □ hours	Uncertainty Range pers □ ppm □ hours	% of total positive contribution	Comments and reference on uncertainty
CH₄				
CH ₄ from in-house storage	0.083	[0.007 – 0.17]	51.9%	Based on IPCC (2006). If IPCC data for < 1 month storage had been chosen, the emissions would be a factor 5.67 times lower. In addition, an uncertainty on a factor 2 is assumed as on the other data from IPCC (2006), see below.
CH ₄ from "Storage" (in pre-tank and outdoor storage)	0.049	[0.02 – 0.15]	30.6%	Data based on IPCC (2006). IPCC (2006) does not estimate the uncertainty. The uncertainty must be high – the emissions depend on storage time which is not included in the IPCC model. Estimated uncertainty: A factor 3.
NO_x				
NO _x from slurry (in-house, storage, and field)	0.024	[0.012-0.048]	15%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 3 (the values in the study are very rough estimates).
NO _x from electricity for pumping and stirring	0.0003	[0.0002-0.0007]	0.2%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NO _x from transport	0.003	[0.001-0.005]	1.6%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NO _x from avoided production of fertilisers	-0.013	[-0.007 – 0.026]	-8.2%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Residue				
Residue from other processes	Approx. 0	Not estimated	< 1%	
TOTALS				
Total POSITIVE contributions	0.159	[0.08-0.32]	100%	Rough estimate: A factor 2
Total AVOIDED contributions	-0.015	[-0.008-0.030]	-9.5%	Rough estimate: A factor 2
Total NET contribution (= positive - negative)	0.14	[0.07-0.29]	90.5%	Rough estimate: A factor 2

3.4.8 Respiratory inorganics (small particles)

The contributions to respiratory inorganics are totally dominated by contributions from NH₃. Nitrogen oxides from transport and production of electricity contribute with less than 7%. The uncertainty on the NH₃ emissions is discussed above under Acidification.

The avoided contributions from the replaced mineral fertilisers are relatively unimportant. Contributions from transport are also unimportant (3%), as well as the contribution from electricity consumption (less than 0.5%).

The unit for respiratory inorganics is PM 2.5 which means that the impacts for this category is characterised in relation to the impact on the respiratory functions on humans from particulate matter with a size of 2.5µ.

Table 3.11.

Contributions to respiratory inorganics from pig slurry in the reference scenario. Per 1000 kg of slurry "ex animal". The % should be taken with care due to the high uncertainties – it is rather rough estimates! The number of digits is *not* an expression of the uncertainty.

Contributions to respiratory inorganics	kg PM 2.5 eq.	Uncertainty Range kg PM 2.5 eq.	% of total positive contribution	Comments and reference on uncertainty
NH₃				
NH ₃ from in-house storage	0.157	[0.08 – 0.31]	54.3%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NH ₃ from "Storage" (in pre-tank and outdoor storage)	0.016	[0.008 – 0.032]	5.6%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NH ₃ from field	0.08	[0.04 – 0.16]	27.8%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Avoided NH ₃ from avoided mineral fertilisers	-0.015	[-0.008 – -0.03]	-5.3%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NO_x				
NO _x from slurry (in-house, storage, and field)	0.024	[0.012 – 0.048]	8.4%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NO _x from electricity for pumping and stirring	0.0005	[0.0003-0.001]	0.2%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NO _x from transport	0.0029	[0.0014-0.0057]	1.0%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NO _x from avoided production of fertilisers	-0.013	[-0.0063- -0.025]	-4.4%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Particulates				
Particulates from transport	0.0038	[0.0019 – 0.0076]	1.3%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Particulates from electricity production	0.00023	[0.0001 – 0.0005]	0.1%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Avoided particulates due to avoided production of mineral fertilisers	-0.015	[-0.007- -0.029]	-5.1%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Residue				
Residue from other processes	-0.004	Not estimated	<2%	
TOTALS				
Total POSITIVE contributions	0.288	[0.14-0.58]	100%	Rough estimate: A factor 2
Total AVOIDED contributions	-0.050	[-0.02— 0.10]	-17.3%	Rough estimate: A factor 2
Total NET contribution (= positive - negative)	0.238	[0.12-0.48]	82.7%	Rough estimate: A factor 2

Table 3.12.

Contributions to respiratory inorganics from dairy cow slurry in the reference scenario. Per 1000 kg of slurry "ex animal". The % should be taken with care due to the high uncertainties – it is rather rough estimates! The number of digits is *not* an expression of the uncertainty.

Contributions to respiratory inorganics	kg PM 2.5 eq.	Uncertainty Range kg PM 2.5 eq.	% of total positive contribution	Comments and reference on uncertainty
NH₃				
NH ₃ from in-house storage	0.081	[0.04 – 0.16]	32.3%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NH ₃ from "Storage" (in pre-tank and outdoor storage)	0.019	[0.01 – 0.04]	7.6%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NH ₃ from field	0.12	[0.06 – 0.23]	45.9%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Avoided NH ₃ from avoided mineral fertilisers	-0.016	[-0.008 – -0.03]	-6.5%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NO_x				
NO _x from slurry (in-house, storage, and field)	0.025	[0.013 – 0.051]	10%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NO _x from electricity for pumping and stirring	0.0004	[0.0002-0.0007]	0.1%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NO _x from transport	0.0028	[0.0014-0.0055]	1.1%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
NO _x from avoided production of fertilisers	-0.014	[-0.0069- -0.028]	-5.5%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Particulates				
Particulates from transport	0.0037	[0.0018 – 0.0073]	1.5%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Particulates from electricity production	0.00016	[0.0001 – 0.0003]	0.1%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Avoided particulates due to avoided production of mineral fertilisers	-0.016	[-0.008- -0.032]	-6.4%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Residue				
Residue from other processes	-0.004	Not estimated	<2%	
TOTALS				
Total POSITIVE contributions	0.252	[0.13-0.50]	100%	Rough estimate: A factor 2
Total AVOIDED contributions	-0.054	[-0.03— 0.11]	-21.5%	Rough estimate: A factor 2
Total NET contribution (= positive - negative)	0.198	[0.10-0.40]	78.5%	Rough estimate: A factor 2

3.4.9 Non-renewable energy resources

The non-renewable energy resources are calculated by use of the LCA method Impact 2002+ (Humbert et al. 2005). The unit is "MJ Primary Energy", using the upper heating value.

The choice of replaced fertilisers has significance for the overall consumption of non-renewable resources. Changing the replaced fertilisers can reduce the net consumption of non-renewable resources by 30% or increase the net consumption by 50%.

Table 3.13.

Consumption of non-renewable energy resources from management of pig slurry in the reference scenario. Per 1000 kg of slurry "ex animal". The % should be taken with care due to the high uncertainties – it is rather rough estimates! The number of digits is *not* an expression of the uncertainty.

Consumption of non-renewable energy resources	MJ primary energy	Uncertainty Range MJ primary energy	% of total positive contribution	Comments and reference on uncertainty
MJ Primary Energy				
Electricity for pumping and stirring	56	[28-112]	37%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Transport	56	[28-112]	37%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Field processes (tractor for application of slurry)	40	[20-80]	26%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Avoided production of mineral fertilisers	-369	[-184-737]	-244%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Residue				
Residue from other processes	0	Not estimated	0%	
TOTALS				
Total POSITIVE contributions	151	[75-300]	100%	Rough estimate: A factor 2
Total AVOIDED contributions	-369	[-180-740]	-244%	Rough estimate: A factor 2
Total NET contribution (= positive - negative)	-217	[-110-440]	-144%	Rough estimate: A factor 2

Table 3.14.

Consumption of non-renewable energy resources from management of dairy cow slurry in the reference scenario. Per 1000 kg of slurry "ex animal". The % should be taken with care due to the high uncertainties – it is rather rough estimates! The number of digits is *not* an expression of the uncertainty.

Consumption of non-renewable energy resources	MJ primary energy	Uncertainty Range MJ primary energy	% of total positive contribution	Comments and reference on uncertainty
MJ Primary Energy				
Electricity for pumping and stirring	40	[20-80]	30%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Transport	54	[27-107]	41%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Field processes (tractor for application of slurry)	38	[19-76]	29%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Avoided production of mineral fertilisers	-410	[-205-820]	-312%	Uncertainty not stated. It is estimated that the uncertainty for this is a factor 2.
Residue				
Residue from other processes	0	Not estimated	0%	
TOTALS				
Total POSITIVE contributions	131	[66-260]	100%	Rough estimate: A factor 2
Total AVOIDED contributions	-410	[-205-820]	-312%	Rough estimate: A factor 2
Total NET contribution (= positive - negative)	-279	[-140-560]	-212%	Rough estimate: A factor 2

3.5 Conclusion

It should be emphasised that essential assumptions and data in this report are chosen to represent Danish conditions only. Results cannot be immediately transferred to other countries due to differences in housing systems, retention time for the slurry in the housing units and in the outdoor storage, differences in how the slurry is stored (covered / uncovered), differences in temperatures, slurry composition (due to differences in the feeding of the animals), temperature and other weather conditions (during and after application), soil types and many other factors.

The conclusions are only valid for the preconditions described in this report! For example, differences in application method to the field, uncovered outdoor storage or differences in the slurry composition will significantly affect the results.

Apparently, the Danish scientific research in the “slurry management area” so far has to a high degree focussed on NH_3 emissions, whereas emissions related to global warming has a higher uncertainty and needs more research. However, it can be concluded that CH_4 emissions from the indoor storage of slurry, the CH_4 emissions from the outdoor storage and the N_2O emissions from the field has great significance for the overall contributions to global warming, and effort to reduce these are important.

The relative contributions to the global warming in table 3.3 and 3.4 should be interpreted with care due to high uncertainties on the data. Contributions to global warming mainly come from CH_4 from in-housing storage, outdoor storage and from CO_2 and N_2O emissions after application of the slurry to the field. Scientific research is needed in the area.

The contribution to acidification is totally dominated by NH_3 emissions in the housing units, during outdoor storage and after application of the slurry to the field.

Aquatic eutrophication (N) is dominated by N leaching. NH_3 emissions also contribute to some extent (contributions from the indoor storage are due to NH_3 emissions).

The uncertainty on aquatic phosphorous eutrophication (P) is high due to lack of data and it *cannot* be concluded that there is a “net saving on P leaching” by applying pig slurry or dairy cow slurry! The discussion of P leaching from slurry vs. mineral fertilisers is beyond the scope of this study.

The main contributor to ozone formation is the CH_4 emissions from the in-house storage of slurry and the outdoor storage of slurry.

The contributions to respiratory inorganics are totally dominated by contributions from NH_3 .

The electricity consumption (for pumps and stirring) is rather insignificant (but for resource consumption).

Transport has a small contribution to the category “Resource consumption” due to the fuel consumption. The contributions to “Ozone formation” are rather small, and so are the contributions to the category “Respiratory

inorganics” (caused by small particles emitted during driving). Transport is totally insignificant for the rest of the impact categories.

The difference between soil type JB3 and JB6 is only noteworthy for aquatic eutrophication (N) (nitrate leaching).

4 Acidification of slurry

The life cycle assessment in this chapter is performed in order to answer the question: “What are the environmental benefits and disadvantages of acidification of slurry in the Infarm NH₄⁺ plant compared to the reference scenario for slurry?”.

This is done by comparing the environmental impacts from the scenario for acidification of slurry in the Infarm NH₄⁺ plant to the environmental impacts from the reference scenario in chapter 3. The Life Cycle Inventory data and the acidification scenario are described in Annex B.

The environmental impacts and conclusions in this chapter build to a great extent on data and information delivered by the producer of the technology, Infarm, or on data made for Infarm. The conclusions rely on this information, and the authors have not had the possibility of verifying the data.

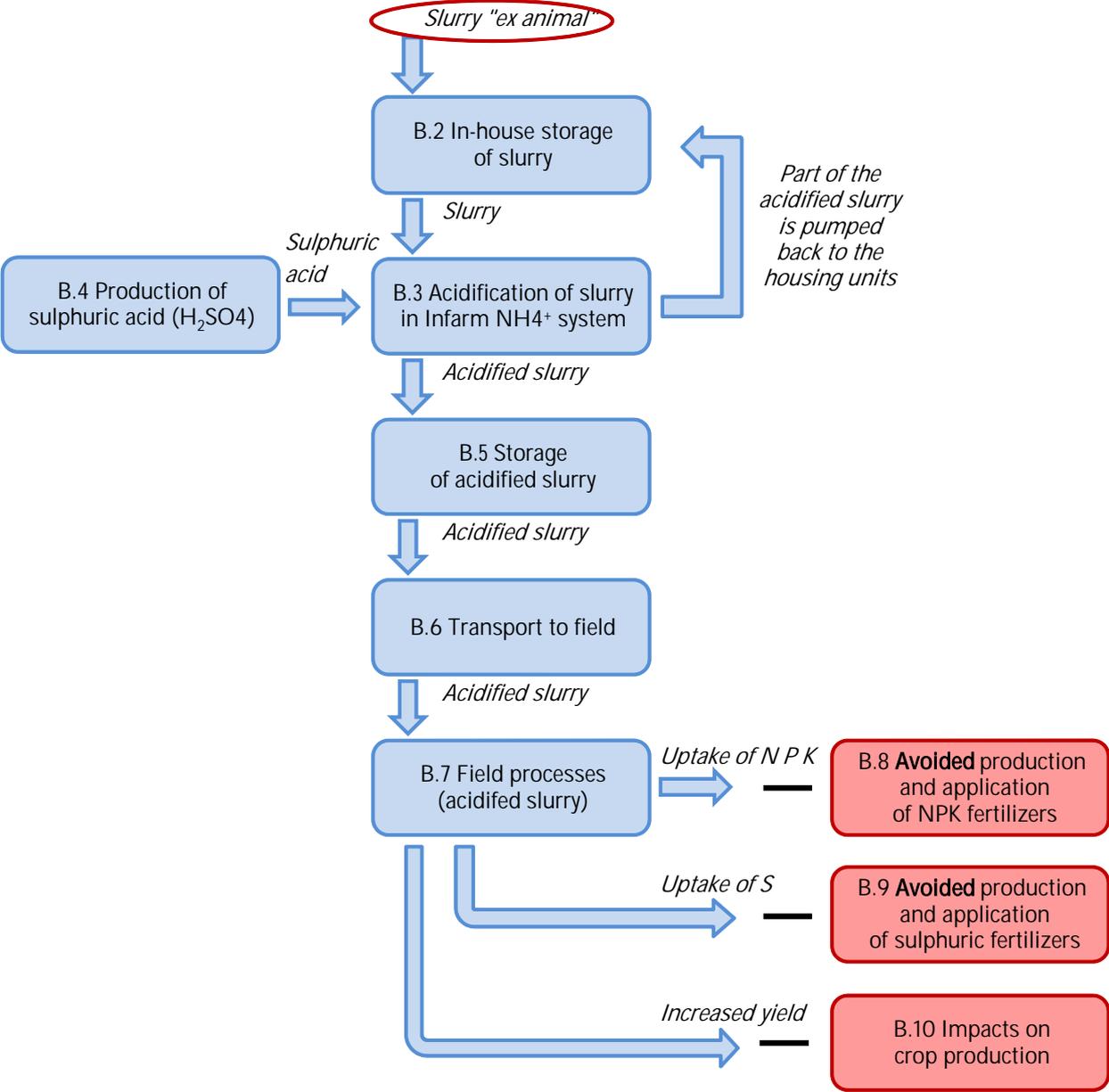
4.1 System description

In the Infarm NH₄⁺ Acidification plant, pig or cattle slurry is acidified by the addition of sulphuric acid (H₂SO₄). The sulphuric acid reduces the pH and the chemical equilibrium between ammonium (NH₄⁺) and ammonia (NH₃) is changed which means that it is primarily in the form of ammonium (NH₄⁺). As only ammonia (NH₃) evaporates, the pH of the slurry is a determining factor for the amount of nitrogen / ammonia that volatilize in the housing system, during storage and during application to fields. Moreover, acidification of the slurry has significance for other factors. For example the use of sulphuric acid for the acidification might be an advantage as it adds sulphur to the field which can have a fertiliser effect.

The system for acidification of slurry is shown in figure 4.1. The numbers in the figure refer to the number of the process (which appears in the figures with the results) and to the corresponding numbers of the process description in Annex B.

For fully understanding of the system for acidification, Annex B should be read before reading the results in section 4.2 below.

Figure 4.1.
Flow diagram for the scenario for acidification of slurry.



4.2 Results of the Impact Assessment

4.2.1 Overall results of the comparison

In figure 4.2, the environmental impacts from Acidification of pig slurry in an Infarm NH4+ plant has been compared to the environmental impacts from the reference system described in chapter 3. Figure 4.3 shows the results for dairy cow slurry.

The results are discussed in the following sections.

Figure 4.2.

Environmental impacts for the system with acidification of slurry in an infarm NH₄⁺ plant compared to the reference system (both based on soil type JB3) – pig slurry.

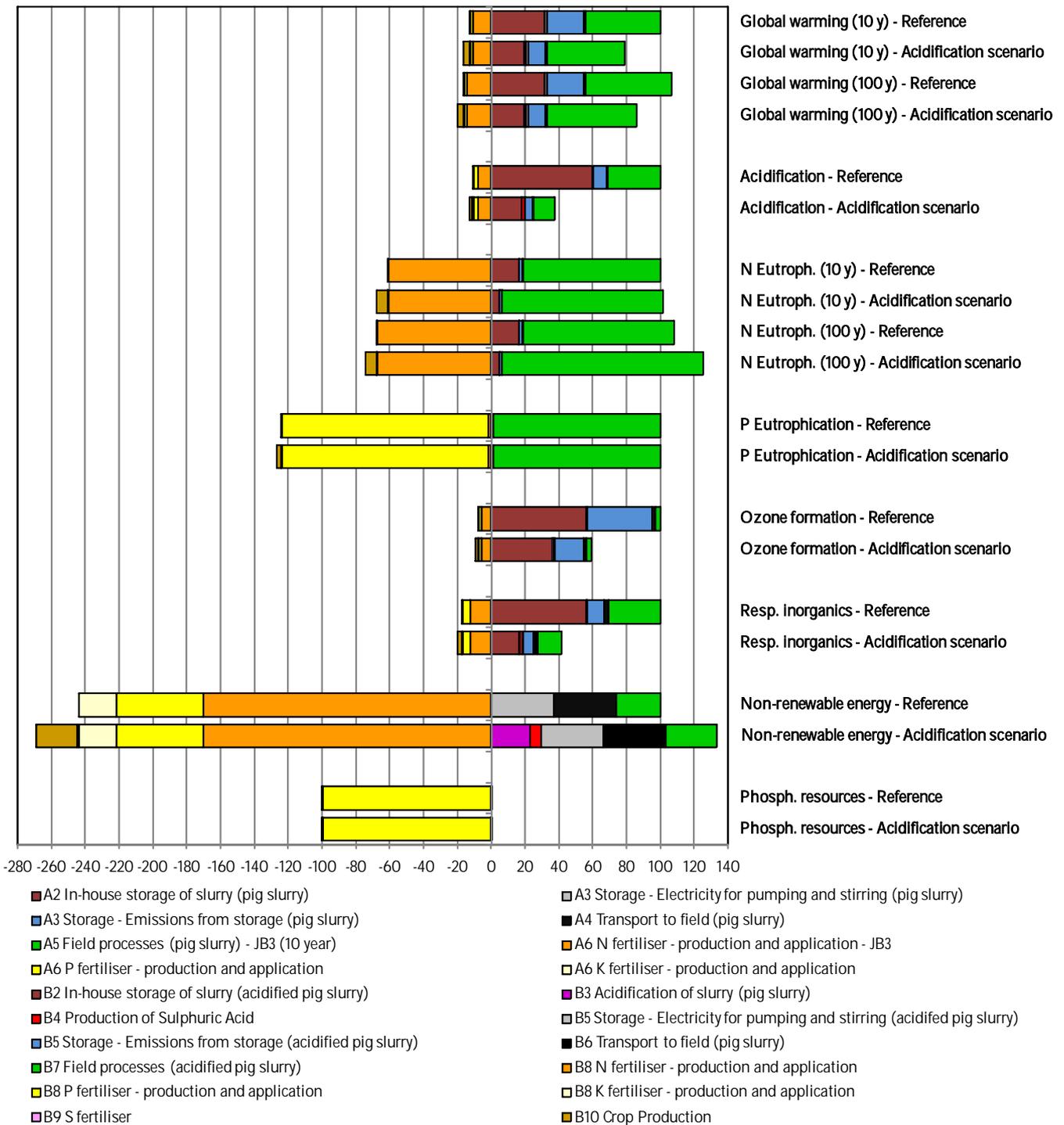
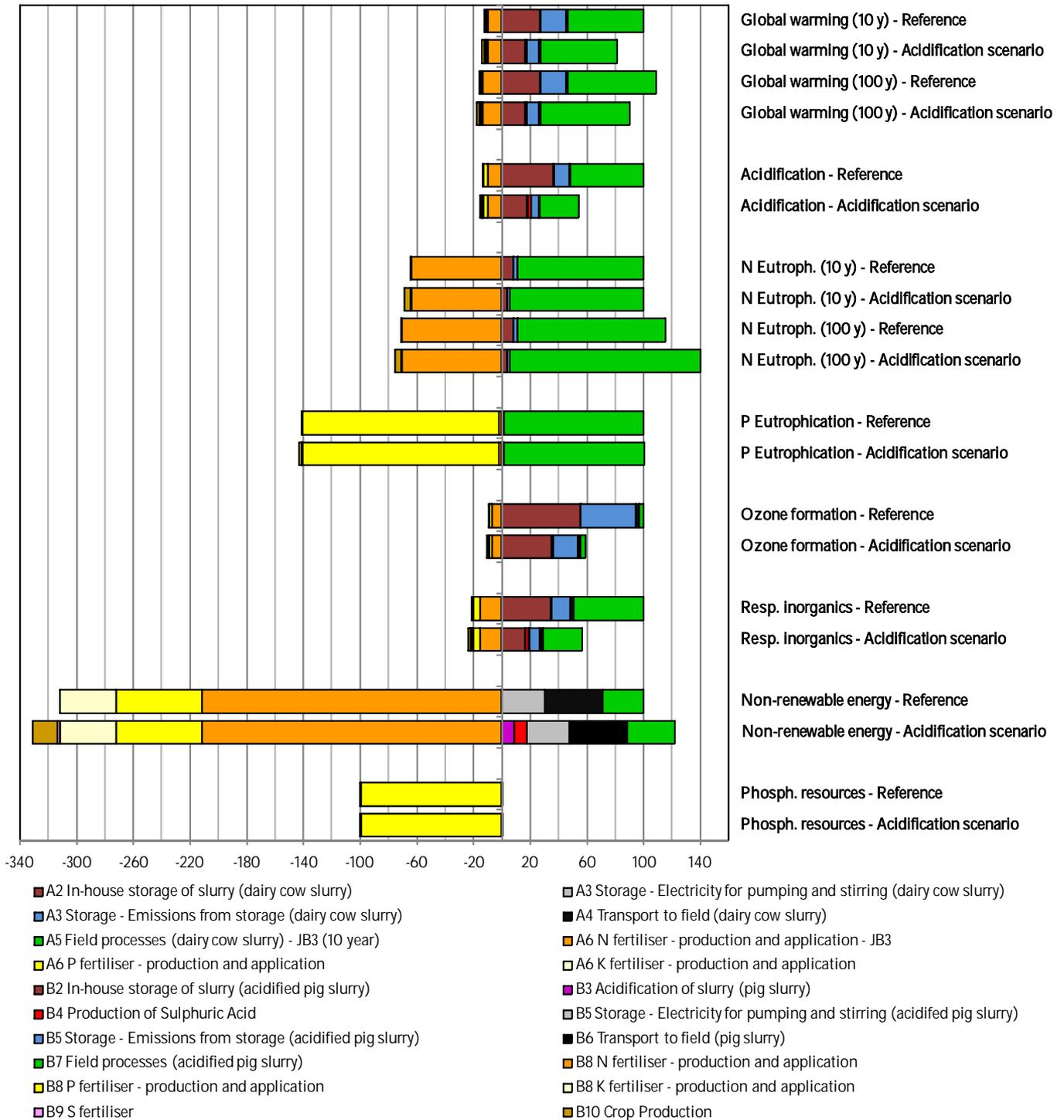


Figure 4.3.

Environmental impacts for the system with acidification of slurry in an infarm NH4+ plant compared to the reference system (both based on soil type JB3) – dairy cow slurry.



4.2.2 Sensitivity analysis

Sensitivity analysis has been carried out for a number of possible variations of the acidification scenario and uncertainties related to the data. Some of the results of the sensitivity analyses are shown in figures in this section, as the influence are complex. For simple variations, the results of the sensitivity analyses are described in the text under each impact category in the following sections.

In this section, the results of sensitivity analysis are shown for:

- The difference between soil type JB3 and JB6.
- Uncertainty on the in-housing CH₄ emissions (based on IPCC data) and the consequence for the comparison.
- Uncertainty on the reduction of the in-housing CH₄ by acidification of the slurry.
- Uncertainty on the CH₄ emissions from storage.
- The assumption that a future law might require that the farmers reduce the consumption of mineral N fertiliser in correspondence with the extra amount of N that the acidified slurry contains compared to non-treated slurry.

The significance of applying a 10 years horizon or 100 year horizon is shown in figure 4.2 and 4.3.

As can be seen from figure 4.4, the difference between soil type JB3 and JB6 has no significance for the overall conclusions. The same applies for dairy cow slurry. Accordingly it has been decided not to include the figures for dairy cow slurry.

The results of the sensitivity analyses are discussed under each impact category in the following sections.

It has not been possible to perform an extensive sensitivity analysis for the variations in slurry composition. However, it can be stated, that for the comparison between the system with acidified slurry and the reference system, the actual content of N and C in itself is not very important, as the emissions for acidified slurry is calculated relative to the reference slurry (in % of the reference slurry). Neither does the amount of water (or rather – the lack of water in the Danish Norm data) influence the overall results of the comparison. However, the C:N ratio is very significant for the dynamics of N after application, strongly influencing the fraction of N going to respectively the soil organic pool (higher with high C:N ratio), N harvest (lower with higher C:N ratio) and leaching (normally lower with higher C:N ratio). Again, as the acidified slurry is calculated relative to the untreated slurry, it is assumed that for most slurry types, it would not change the overall conclusions.

Figure 4.4.
 Sensitivity Analysis: Difference between soil type JB3 and JB6.
 Environmental impacts for the system with acidification of slurry in an infarm NH4+ plant compared to the reference system – pig slurry.

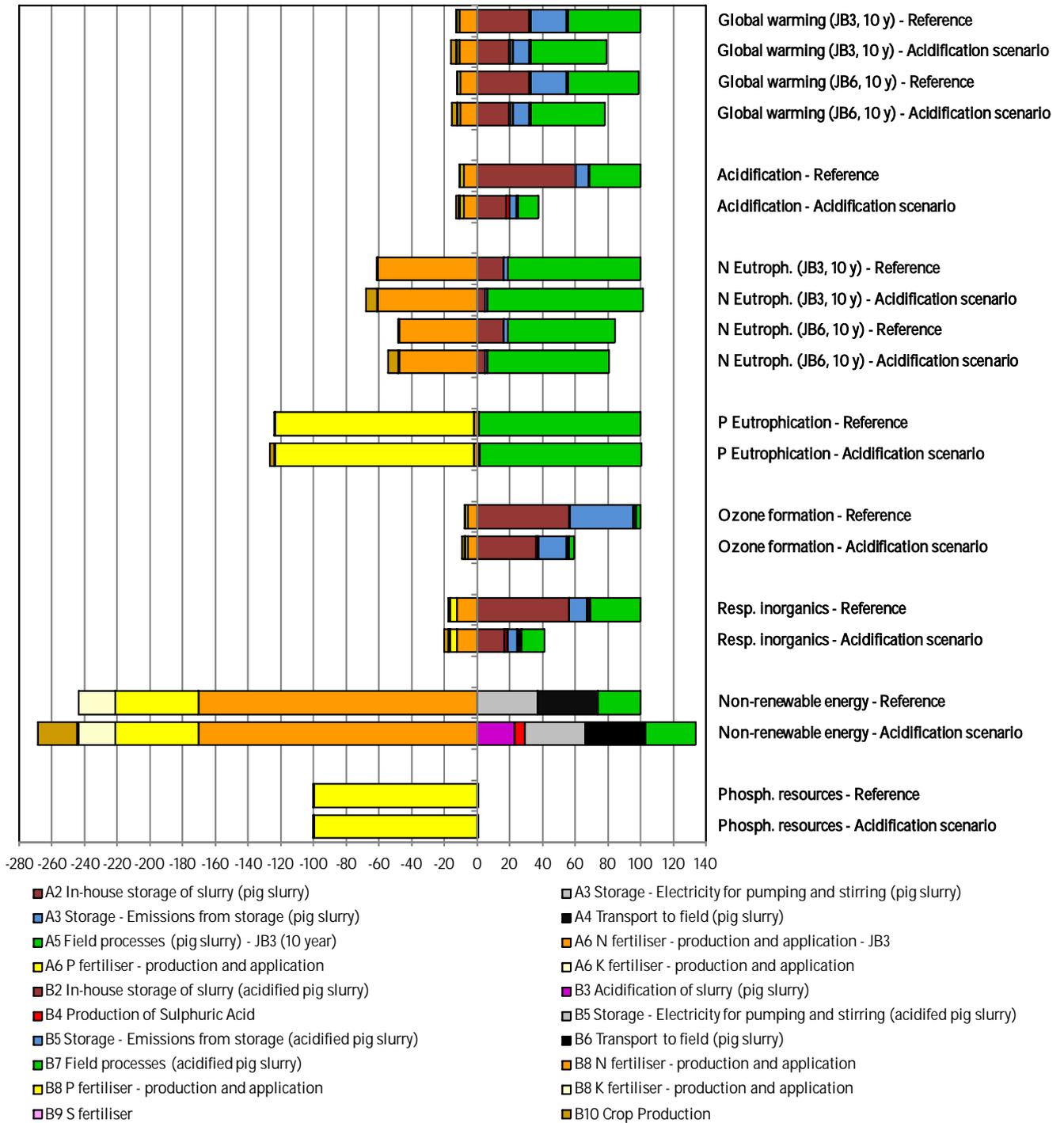


Figure 4.5.

Sensitivity Analysis: Consequences of choice of IPCC data for in-house CH4 emissions for a retention time > 1 month compared to data for a retention time < 1 month.

Environmental impacts for the system with acidification of slurry in an infarm NH4+ plant compared to the reference system (both based on soil type JB3, 10 year time horizon for soil processes) – pig slurry.

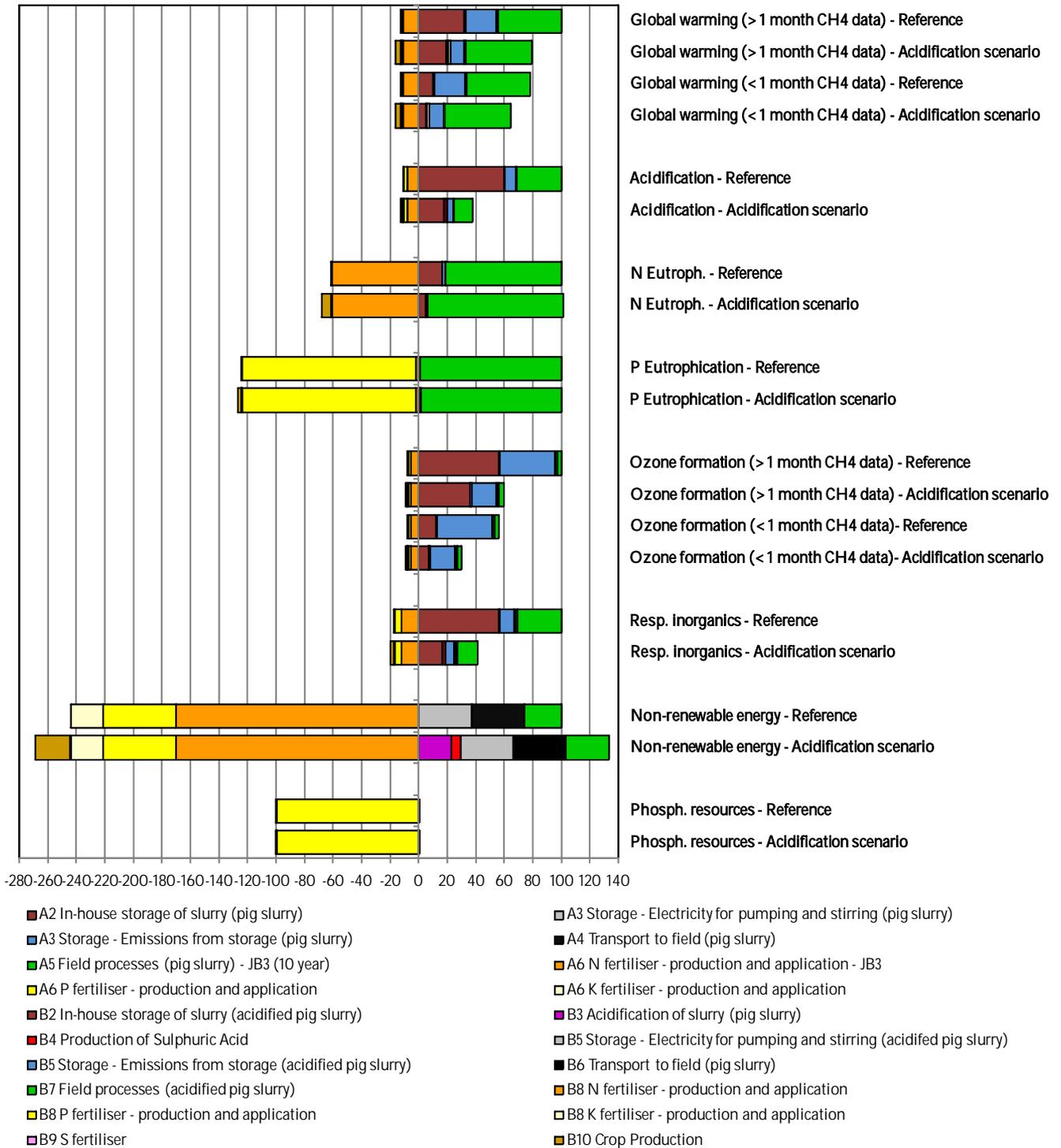


Figure 4.6.

Sensitivity Analysis: Consequences of changes in the reduction of the in-house CH₄ emissions caused by the acidification of slurry.

Environmental impacts for the system with acidification of slurry in an infarm NH₄⁺ plant compared to the reference system (both based on soil type JB3, 10 year time horizon for soil processes) – pig slurry.

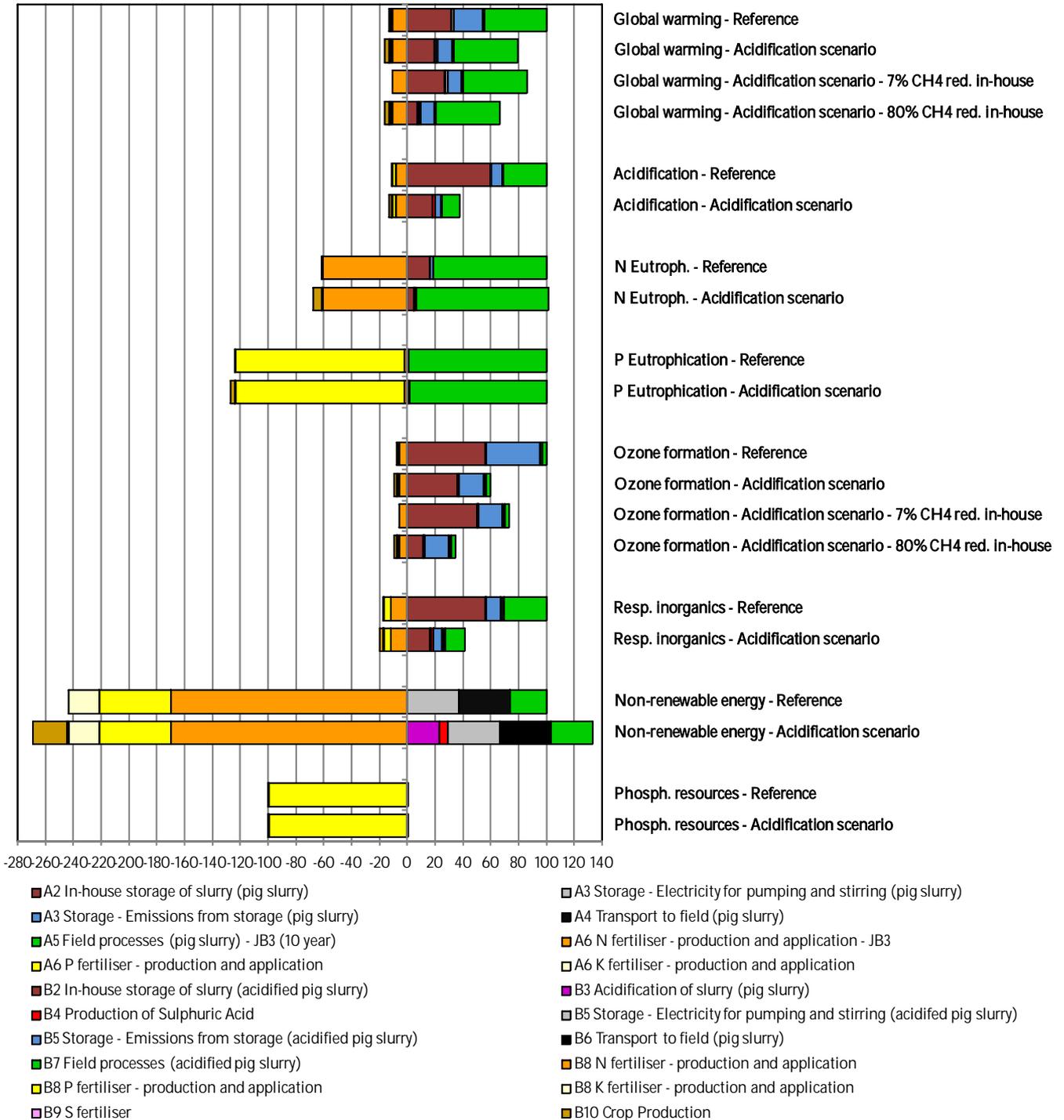


Figure 4.7.

Sensitivity Analysis: Consequences of changes in the reduction of the CH₄ emissions from storage caused by the acidification of slurry.

Environmental impacts for the system with acidification of slurry in an infarm NH₄⁺ plant compared to the reference system (both based on soil type JB3, 10 year time horizon for soil processes) – pig slurry.

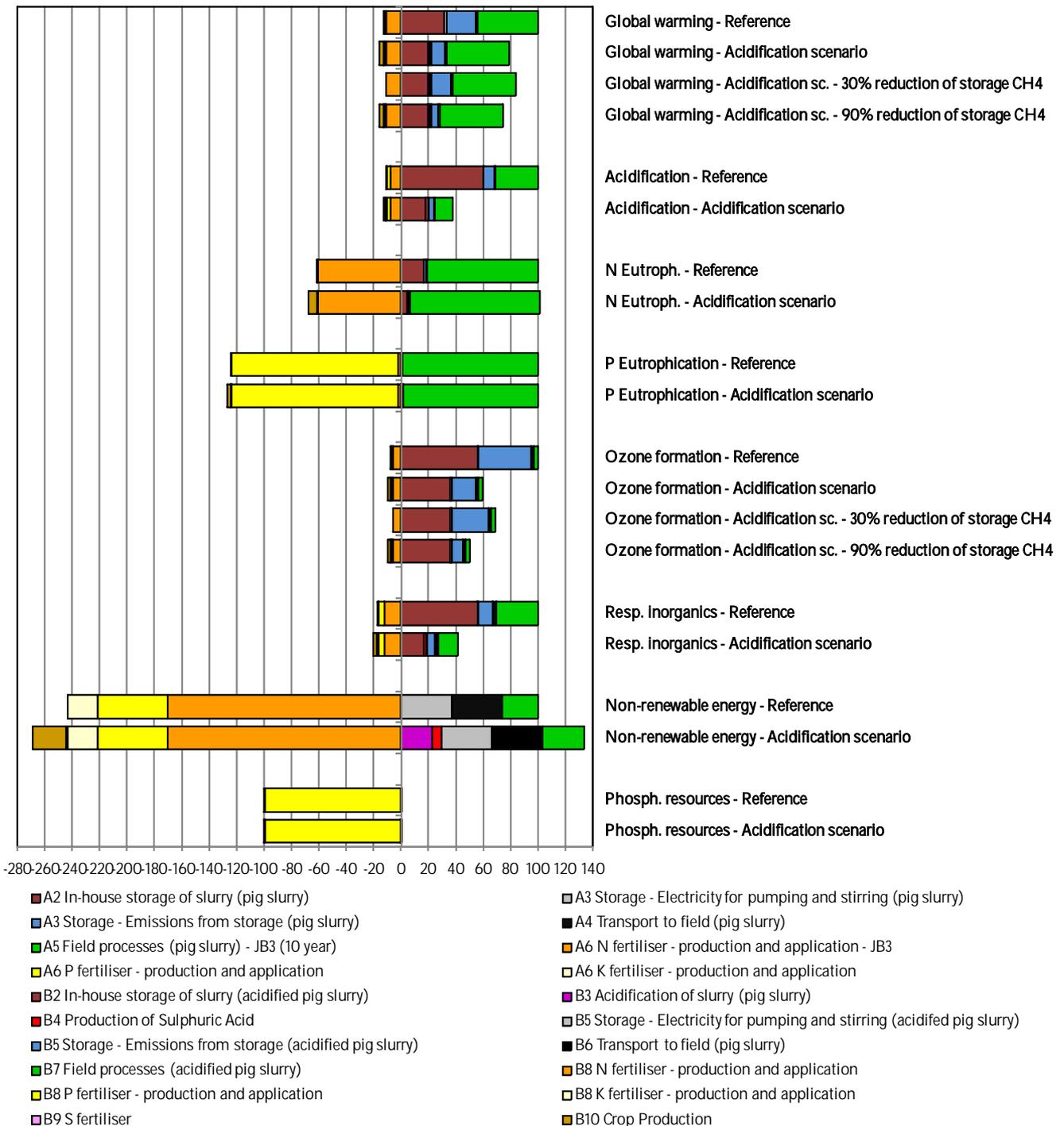


Figure 4.8.

Sensitivity Analysis: Consequences of changing the law so it demands that the farmer reduces the consumption of mineral N fertiliser in correspondence with the extra amount of N that the acidified slurry contains compared to non-treated slurry.

Environmental impacts for the system with acidification of slurry in an infarm NH₄⁺ plant compared to the reference system (both based on soil type JB3, 10 year time horizon for soil processes) – pig slurry.

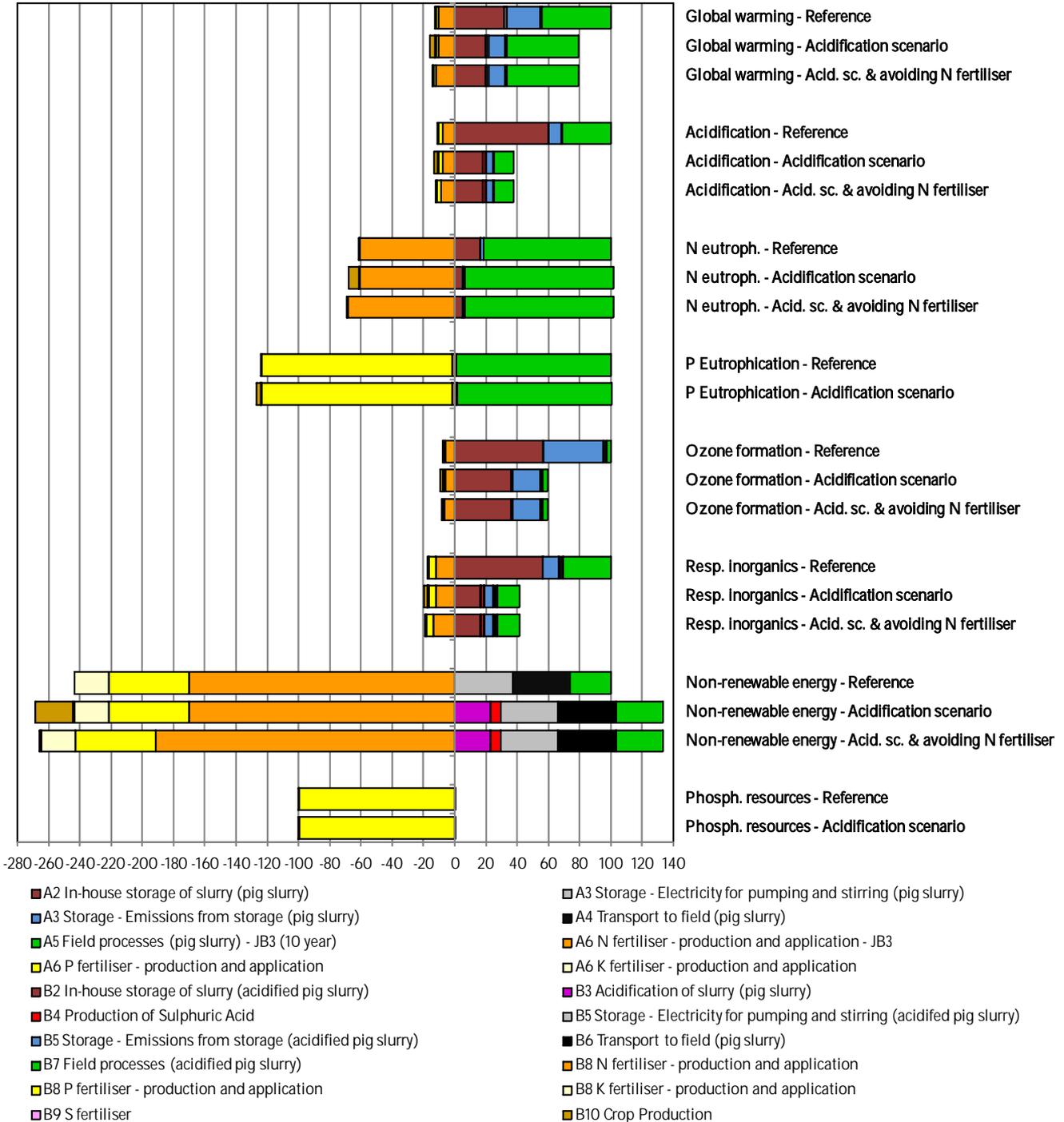
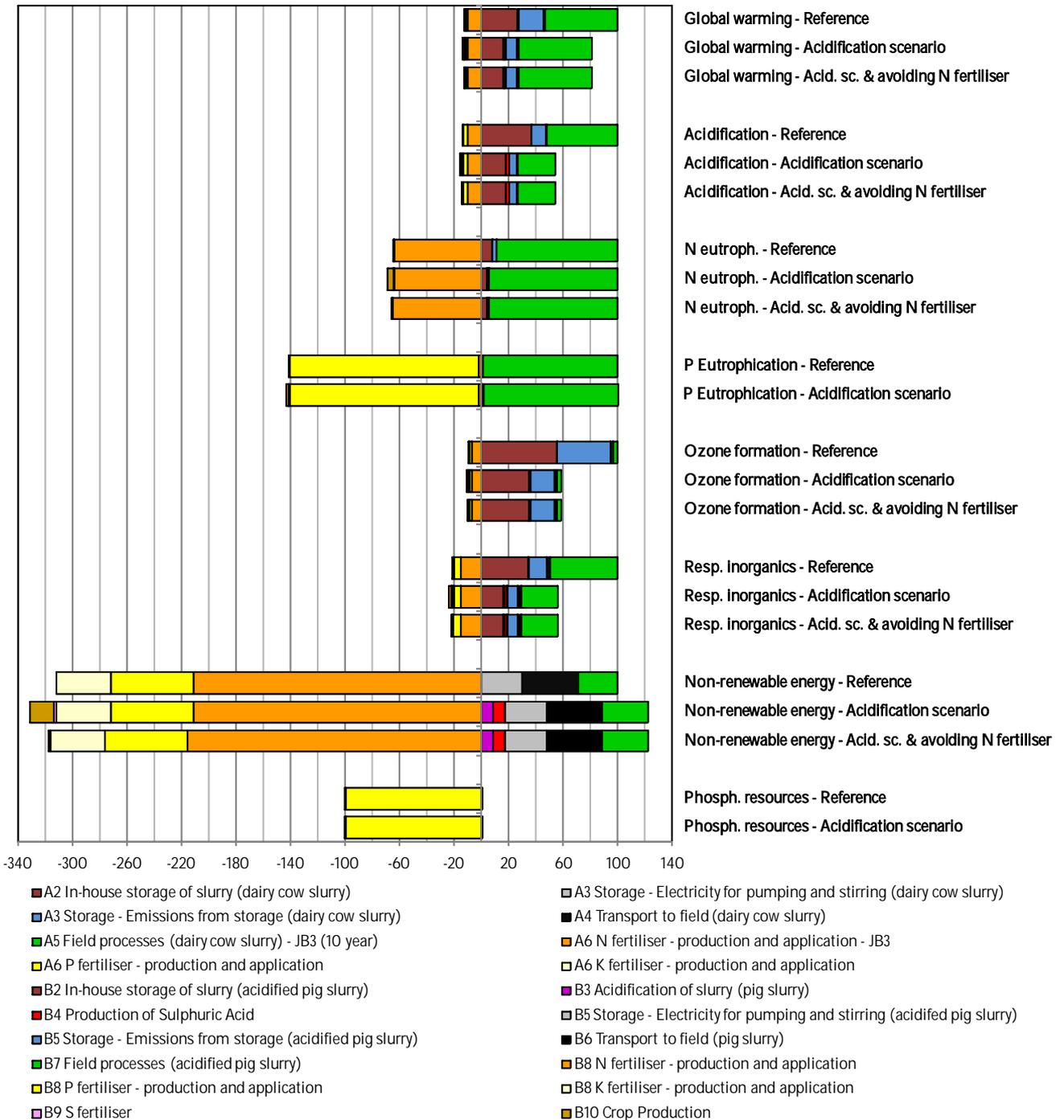


Figure 4.9.

Sensitivity Analysis: Consequences of changing the law so it demands that the farmer reduce the consumption of mineral N fertiliser in correspondence with the extra amount of N that the acidified slurry contains compared to non-treated slurry.

Environmental impacts for the system with acidification of slurry in an infarm NH4+ plant compared to the reference system (both based on soil type JB3, 10 year time horizon for soil processes) – *dairy cow slurry*.



4.2.3 Global warming

In figure 4.2 and 4.3 it is seen that the “acidification scenario” has a lower contribution to global warming. The lower contribution is due to a decrease of the CH₄ emissions in the housing units and during the outdoor storage (which probably is caused by microbial activity being inhibited to some extent at low pH). However, it should be emphasised that the decrease is based on a few laboratory measurements under laboratory conditions, rather than “real outdoor conditions”, and the magnitude of the relative decrease should be interpreted with care. The decrease could be higher: However, the decrease could also be lower, as described in Annex B.

As mentioned in Annex A, the uncertainty on the CH₄ emissions is high, and this has influence on the comparison. As mentioned, the IPCC (2006) model use a very rough partitioning in “storage < 1 month” and “storage > 1 month”. The emission factors (in kg CH₄ per kg VS) is 5.67 times higher for “storage > 1 month” than for “storage < 1 month” which is an unrealistic jump. In this study, the high emission factor from IPCC (2006) has been used as a conservative estimate. If the lower emission factor was used, the contribution from the housing units would be significantly smaller, and so would the relative reduction by the acidification of the slurry compared to the total contribution from the entire system. The sensitivity analysis for this is shown in figure 4.5. The uncertainty has significance for the absolute reduction, but less significance for the relative reduction. The choice of the higher IPCC value might overestimate the absolute net reduction by the acidification scenario in CO₂-equivalents (for global warming). This consideration is included in table 4.1 and 4.2 for the net reductions in section 4.3

The data on the factor by which acidification of slurry reduces the in-house CH₄ emissions are based on very few measurements and the uncertainty is rather high. The uncertainty on the reduction factor affects the contribution to global warming and to photochemical ozone formation. Sensitivity analyses have been carried out with a reduction factor of 7% and 80% and the results are shown in figure 4.6. Preliminary measurements indicate that the reduction is probably rather high, as the measurements on the reductions include CH₄ emissions from “enteric fermentation” from dairy cows. When comparing data for the CH₄ emissions from “enteric fermentation” from dairy cows (Nielsen et al, 2008a, table 6.6) with the CH₄ emissions from “manure management” (Nielsen et al, 2008a, table 6.12) it can be seen that the CH₄ from the slurry is in the order of 13% of the total CH₄ emissions from dairy cows. As the CH₄ from the enteric fermentation is not included in this study (as slurry management does not influence this), it is likely, that the CH₄ reductions from the slurry in the housing units could be rather high. As no data have been available, a rough estimate has been used for the sensitivity analysis, assuming a reduction of 80% of the CH₄ emissions from the slurry. However, scientific research is needed in order to evaluate the reduction factor. From figure 4.6 it can be seen that the influence on the total contribution to global warming and photochemical ozone formation is noteworthy.

The data for the reduction of CH₄ emissions from storage of the slurry are also rather uncertain, as described in Annex B (section B.5). For the “base case” acidification scenario, it is assumed that acidification reduces the CH₄ emissions by 60%. Sensitivity analysis has been carried out for a reduction of

30% and 90% in figure 4.7. From figure 4.7 it is obvious, that improved scientific data is needed for the documentation of the CH₄ reductions from acidification, as it is important for the overall reductions.

As mentioned in Annex B, it is assumed that the N₂O emissions from application of acidified slurry to the field are at the same level as untreated slurry (i.e. the emission factor for N₂O per kg N). It is, however, an assumption without any reference to measurements or testing. It is likely that the N₂O emissions will be changed for acidified slurry, however, there is no indication of whether the emission factor is higher or lower than for untreated slurry. Scientific research is needed in the area.

The conclusion on global warming is, that preliminary results indicate a reduced production of CH₄ during storage of acidified slurry, but the magnitude of this is uncertain as the results build on a few measurements (*“Der foreligger kun et særdeles spinkelt grundlag for at vurdere virkningen af forsuring på dannelsen af drivhusgasser”*) as emphasized in the upcoming BAT-documentation (which have been sent for public hearing until 15 April 2009 (revised version of 23 March 2009 for pig slurry and revised version of 17 March 2009) (BAT (2009a) and BAT (2009b)). The reduction of global warming reduction could be counteracted by an increase from field emissions if the N₂O emissions from the application of acidified slurry are somewhat higher than N₂O from untreated slurry.

The acidification of slurry has a potential of reducing the contribution to global warming significantly compared to the reference system. As can be seen in table 4.1 and 4.2 in section 4.3, the reduction is probably in the magnitude of 10-30% of the total contributions to global warming from the slurry in the reference system. However, scientific research is needed on field study level, both in the area of CH₄ emissions from in-house storage and outdoor storage and in area of N₂O emission from application of acidified slurry before a clear conclusion on the magnitude of the overall reductions of the contribution to global warming can be made.

4.2.4 Acidification (the environmental impact)

When comparing the system with acidified slurry with the reference slurry in figure 4.2 and 4.3, it is apparent that the contribution to the environmental impact “Acidification” is significantly reduced for the system with acidified slurry. As described in section 3.3 the contribution to the environmental impact “Acidification” is totally dominated by NH₃ emissions and the acidification of slurry reduce the NH₃ emissions significantly.

Even when taking the uncertainties into consideration, it can be concluded that the reduced NH₃ emissions lead to a reduced contribution to the environmental impact “Acidification”.

4.2.5 Aquatic eutrophication (N)

As can be seen in figure 4.2 and 4.3 the contributions to aquatic eutrophication (N) for the acidified slurry scenario are at the same level as the reference scenario (at a 10 years perspective) or higher (at a 100 years perspective). This is due to a higher N content in the slurry, leading to a higher nitrate leaching. On a 10 year basis, the increase is counteracted by a subtraction of “crop production”. This is due to the assumption that application of acidified slurry to fields leads to a higher crop yield. The

assumption is based on field tests combined with the fact that the acidified slurry has a higher content of N. As the Danish law is today, this does not lead to farmers having to subtract a higher amount of N in their accounts. Accordingly, they are allowed to apply the same amount of N in mineral fertilisers to the field as for untreated slurry. As a consequence the field receives more N, leading to a higher crop yield. As the systems have to be equal in order to be comparable a corresponding amount of crop is subtracted from the system with acidified slurry. The uncertainty on the extra production of crop yield is very high and conclusions on the “net environmental impacts” from the “replaced crop” should be taken with care.

Alternatively, the increased amount of N in the acidified slurry could be subtracted as “replaced mineral N fertiliser”. This would, however, require that the Danish law increased the “replacement value” for N in acidified slurry compared to untreated slurry, having the consequence that the farmer had to subtract a higher amount of N in the N accounts. In that case, there would probably be no increase in the crop yield (as the field would receive the same amount of N as in the reference scenario). The amount of replaced N fertiliser would increase, and the picture for aquatic eutrophication (N) would be approximately the same as when subtracting the crop yield, i.e. a slightly higher amount of aquatic eutrophication can be subtracted from the system. A sensitivity analysis has been carried out for the assumption that a future law demands that the farmer reduce the consumption of mineral N fertiliser in correspondence with the extra amount of N that the acidified slurry contains compared to non-treated slurry. This is shown in figure 4.8. From this it can be seen that the amount of replaced mineral N fertiliser would save significant amounts of N leaching.

On a 100 years perspective, most of the initially accumulated organic matter from slurry and crop residues will be mineralised to, amongst others, mineral nitrogen. This nitrogen will to some extent go to leaching, as outlined in Annex A. Therefore the 100 year leaching levels are higher than the 10 year levels.

At figure 4.4 there is an interesting aspect: For JB6 soil, the *total* contribution to aquatic eutrophication is slightly lower from the acidified slurry than from the reference scenario. The N leaching from the field is still higher for the acidified slurry, however, this is counterbalanced by the reductions of NH_3 in the housing units and during storage (as the airborne NH_3 emissions also contribute to aquatic eutrophication to some extent).

When taking the replaced crop yield into consideration, there is no significant difference between the acidification scenario and the reference scenario on a 10 year basis due to uncertainties. On a 100 year basis, the contribution to nitrate leaching is increased by 10-30% when comparing with the contribution from the reference system.

4.2.6 Aquatic eutrophication (P)

The leaching of phosphorous from application of acidified slurry is assumed to be the same as for application of untreated slurry. As the content of phosphorous is the same, there is no change in the contributions to aquatic eutrophication (P).

4.2.7 Photochemical Ozone Formation (“smog”)

As described in section 3.3, the main contributor to photochemical ozone formation is the CH₄ emissions from the in-house storage of slurry and the outdoor storage of slurry, which means that the photochemical ozone formation in figure 4.2 and figure 4.3 has the same uncertainties as described under global warming.

As described in chapter 3, section 3.4.3 and in Annex A, there are significant uncertainties related to the in-house CH₄ emissions (based on data from IPCC). The sensitivity analysis for this is shown in figure 4.5. As can be seen from the figure, the change of the in-house CH₄ emission has influence on the contributions to global warming and photochemical ozone formation. The absolute reduction by introducing acidification of slurry is less, when the in-house CH₄ emission is calculated as the lower IPCC value, however, the relative reduction for the total systems is approximately at the same level, and as mentioned under global warming, the choice of the lower IPCC value for the in-house CH₄ emission is considered not to be crucial for the conclusions.

As described under global warming, the choice of the higher IPCC value might overestimate the absolute net reduction by the acidification scenario for the photochemical ozone formation in person.ppm.hr (for explanation, see section 3.4.7 regarding Photochemical Ozone Formation).

4.2.8 Respiratory inorganics (small particles)

As described in section 3.3, the contributions to respiratory inorganics are totally dominated by contributions from NH₃. Accordingly, the contributions to respiratory inorganics follow the pattern for acidification.

It means that even when taking the uncertainties into consideration, it can be concluded that as acidification of slurry reduce NH₃ emissions this leads to a reduced contribution to the environmental impact “Respiratory inorganics”.

4.2.9 Non-renewable energy resources

The consumption of non-renewable energy resources is mainly due to transport, energy consumption during application of slurry and electricity. The consumption of electricity for the acidification plant increases the consumption of non-renewable energy resources compared to the reference system.

The increase in consumption of non-renewable energy resources caused by the electricity consumption by the acidification plant is partly counterbalanced by the energy use for the “replaced crop production” (due to the higher crop yield when applying acidified slurry as described under aquatic eutrophication (N)). As the uncertainty on the avoided energy consumption by the “replaced crop production” is rather high, the net consumption of non-renewable energy resources is somewhat uncertain. When taking the uncertainties into consideration, there is no significant difference between the acidification scenario and the reference scenario.

As mentioned above, a sensitivity analysis has been carried out assuming that the Danish Law is changed, leading to a requirement that the “fertiliser replacement value” reflects the actual content of N in the acidified slurry ex

storage. As can be seen from figure 4.8 and 4.9 this does not change the conclusion regarding non-renewable energy resources.

A sensitivity analysis has been carried out for an acidification scenario with considerable higher electricity consumption by the acidification plant. As mentioned in Annex B, the electricity consumption for the acidification plant is 3 kWh per 1000 kg pig slurry and 1 kWh for 1000 kg dairy cow slurry. For at least one of the acidification plants at a pig farm, the energy consumption is considerably higher (Frandsen and Schelde, 2007), and in this case, the consumption of non-renewable energy resources by far exceeds the replaced amounts. The high energy consumption is, however, an exception according to the producer of the acidification plants, Infarm.

4.2.10 Consumption of phosphorus as a resource

There is no difference regarding the consumption of phosphorus as a resource between the Acidification Plant scenario and the reference scenario.

4.3 Conclusion

The life cycle assessment in this chapter is performed in order to answer the question: "What are the environmental benefits and disadvantages of acidification of slurry in the Infarm NH₄⁺ plant compared to the reference scenario for slurry?".

It should be emphasised that the data and conclusions in this report applies for Danish conditions only. Results cannot be immediately transferred to other countries due to differences in housing systems, retention time for the slurry in the housing units and in the outdoor storage, differences in how the slurry is stored (covered / uncovered), differences in temperatures, slurry composition (due to differences in the feeding of the animals), temperature, weather conditions (during and after application), soil types and many other factors.

The conclusions are only valid for the preconditions described in this report. For example, differences in application method to the field, uncovered outdoor storage or differences in the slurry composition will affect the results.

The results of the comparison are shown in table 4.1 and 4.2 (absolute values) and figure 4.10 and 4.11 (relative values).

The results of the comparative life cycle assessment show that:

- Acidification of slurry reduces the NH₃ emissions significantly. As NH₃ gives the main contributions to the environmental impact categories "Acidification" and "Respiratory inorganics", the total contributions to these are reduced considerably when comparing the acidification scenario to the reference. The contribution to "Acidification" is reduced by 40-90% compared to the contribution from the reference system for pig slurry and by 30-66% compared to the contribution from the reference system for dairy cow slurry. The contribution to "Respiratory inorganics" is reduced by 30-90% compared to the contribution from the reference system for pig slurry and by 20-70% compared to the contribution from the reference system for dairy cow slurry.

- Acidification of slurry reduces the CH₄ emissions, probably due to that the biological activity is inhibited at the low pH. This leads to a reduction of the contributions to the environmental impacts “Global warming and “Photochemical ozone formation”. The contribution to “Global warming” is reduced by 10-36% compared to the contribution from the reference systems for pig and dairy cow slurry. The magnitude of the reductions is affected by a high uncertainty on the reductions of the CH₄ emissions and scientific research in the area is required in order to be able to give a clear picture of the magnitude of the reductions. Furthermore, it is not clarified whether acidification of slurry affects the N₂O emissions from field after application – research is also required in this area.
- As the acidified slurry contains more N when applied to fields than untreated slurry (due to the reduced losses of NH₃ during storage), the contribution to nitrate leaching is higher for acidified slurry. The higher amount of N will lead to a higher crop yield. When comparing systems in life cycle assessments, it is very important that the outputs of the compared systems are equal (otherwise they are not comparable. For example, a system that produces 1 kg wheat shall not be compared to a system that produces 1 kg wheat plus 2 kg rye). In order to make the system for acidification of slurry equal to the reference system, a corresponding amount of crop yield has been subtracted from the system, which will to some extent counterbalance the higher nitrate leaching (however, these data are rather uncertain). When taking the replaced crop yield into consideration, there is no significant difference between the acidification scenario and the reference scenario on a 10 year basis due to uncertainties. On a 100 year basis, the contribution to nitrate leaching is increased by 10-30% when comparing with the contribution from the reference system.
- Acidification of slurry does not affect “Aquatic phosphorous eutrophication” or the resource consumption of phosphorus, as acidification does not affect the content of phosphorus in the slurry.
- The consumption of non-renewable energy resources is not significant higher for the acidification scenario as the extra consumption due to the electricity consumption is counterbalanced by the subtraction of the higher crop yield, as explained above.
- Transport contributes to the consumption of non-renewable energy resources, and for the rest of the impact categories, the contribution from transport is not significant. As the transport is the same for the acidification scenario and the reference scenario, it has not significance for the comparison.
- The difference between soil type JB3 and JB6 is only noteworthy for aquatic eutrophication (N) (nitrate leaching). The difference is not significant for the overall results.

Table 4.1.

Comparison of the impacts from the acidification scenario to the reference scenario for pig slurry. The number of digits is *not* an expression of the uncertainty. The uncertainty of the net contribution is based on an estimate with regard to the uncertainty on the data that forms the foundation for the LCA.

Environmental impact / resource consumption	Reference scenario	Acidification scenario	Net contribution i.e. "Acidification scenario" minus "Reference scenario"
Global warming (during 10 years) [kg CO ₂ eq.]	From slurry: 284 kg From fertiliser: -36 kg Net: 248 kg	From slurry: 225 kg From fertiliser: -46 kg Net: 179 kg	-68 [-35 – 100] kg CO ₂ eq. 12-36% reduction of contribution from slurry
Global warming (during 100 years) [kg CO ₂ eq.]	From slurry: 304 kg From fertiliser: -47 kg Net: 257 kg	From slurry: 244 kg From fertiliser: -56 kg Net: 188 kg	-69 [-35 – 100] kg CO ₂ eq. 11-34% reduction of contribution from slurry
Acidification [m ² UES, i.e. area of unprotected ecosystem]	From slurry: 50.3 m ² From fertiliser: -5.5 m ² Net: 44.8 m ²	From slurry: 19.0 m ² From fertiliser: -6.5 m ² Net: 12.5 m ²	-32 [-19- -45] m ² UES 40-90% reduction of contribution from slurry
N-eutrophication (aquatic) (during 10 years) [kg N - amount reaching aquatic recipients]	From slurry: 1.51 kg From fertiliser: -0.93 kg Net: 0.59 kg	From slurry: 1.54 kg From fertiliser ¹ : -1.03 kg Net: 0.51 kg	-0.08 [0 - -0.16] kg N No significant difference due to uncertainties on "avoided crop" (see text)
N-eutrophication (aquatic) (during 100 years) [kg N - amount reaching aquatic recipients]	From slurry: 1.63 kg From fertiliser: -1.03 kg Net: 0.61 kg	From slurry: 1.90 kg From fertiliser: -1.13 kg Net: 0.77 kg	0.17 [0.08 – 0.34] kg N 5-20% increase of contribution from slurry
P-eutrophication (aquatic) [kg P - amount reaching aquatic recipients]	From slurry: 0.0069 kg From fertiliser: -0.0086 kg Difference not significant due to high uncertainties	From slurry: 0.0069 kg From fertiliser: -0.0086 kg Difference not significant due to high uncertainties	No difference
Photochemical ozone formation [person.ppm.hr - see section 3.4.7]	From slurry: 0.18 p.p.h From fertiliser: -0.014 p.p.h Net: 0.17 p.p.h	From slurry: 0.11 p.p.h From fertiliser: -0.017 p.p.h Net: 0.089 p.p.h	-0.075 pers.ppm.hr [-0.038- -0.11] 20-60% reduction of contribution from slurry
Respiratory Inorganics [kg PM2.5 eq, i.e. kg equivalents of 2.5 µm size particles]	From slurry: 0.29 kg From fertiliser: - 0.05 kg Net: 0.24 kg	From slurry: 0.12 kg From fertiliser: - 0.06 kg Net: 0.06 kg	-0.18 [-0.09 – -0.26] kg PM2.5 30-90% reduction of contribution from slurry
Non-renewable energy [MJ primary energy]	From slurry: 151 MJ From fertiliser: - 369 MJ Net: -217 MJ	From slurry: 202 MJ From fertiliser ¹ : - 406 MJ Net: -204 MJ	13 [0 – 39] MJ 0-26% increase of contribution from slurry
Phosphorus Resources [kg P]	From slurry: 0 kg From fertiliser: - 1.3 kg Net: - 1.3 kg	From slurry: 0 kg From fertiliser: - 1.3 kg Net: - 1.3 kg	No difference
Carbon stored in soil during 10 years [kg C]	From slurry: 7.5 kg C From fertiliser: - 3.9 kg C Net: 3.6 kg C	From slurry: 11.0 kg C From fertiliser: - 3.9 kg C Net: 7.1 kg C	3.5 [2.5 – 4.9] kg C 12.9 [9.2 - 18] kg CO ₂
(Corresponding to this amount of CO ₂ -eq.)	From slurry: 27.6 kg CO ₂ From fertiliser: -14.3 kg CO ₂ Net: 13.2 kg CO ₂	From slurry: 40.5 kg CO ₂ From fertiliser: -14.3 kg CO ₂ Net: 26.1 kg CO ₂	33-65% increase of contribution from slurry
Carbon stored in soil during 100 years [kg C]	From slurry: 2.1 kg C From fertiliser: - 1.1 kg C Net: 1.0 kg C	From slurry: 5.9 kg C From fertiliser: - 1.1 kg C Net: 4.8 kg C	3.8 [2.7 – 5.3] kg C 13.7 [9.8 – 19.2] kg CO ₂
(Corresponding to this amount of CO ₂ -eq.)	From slurry: 7.8 kg CO ₂ From fertiliser: -4.0 kg CO ₂ Net: 3.8 kg CO ₂	From slurry: 21.6 kg CO ₂ From fertiliser: -4.0 kg CO ₂ Net: 17.6 kg CO ₂	126 – 246% increase of contribution from slurry

¹ This includes also the avoided N-eutrophication from the “replaced crop production”. As application of acidified slurry increase the crop production, this crop is subtracted from the system. There is a large uncertainty on this factor.

Table 4.2.

Comparison of the impacts from the acidification scenario to the reference scenario for dairy cow slurry. The number of digits is *not* an expression of the uncertainty. The uncertainty of the net contribution is based on an estimate with regard to the uncertainty on the data that forms the foundation for the LCA.

Environmental impact / resource consumption	Reference scenario	Acidification scenario	Net contribution i.e. “Acidification scenario” minus “Reference scenario”
Global warming (during 10 years) [kg CO ₂ eq.]	From slurry: 326 kg From fertiliser: -40 kg Net: 286 kg	From slurry: 265 kg From fertiliser: -46 kg Net: 219 kg	-67 [-33 – 100] kg CO ₂ eq. 10-30% reduction of contribution from slurry
Global warming (during 100 years) [kg CO ₂ eq.]	From slurry: 355 kg From fertiliser: -51 kg Net: 304 kg	From slurry: 293 kg From fertiliser: -57 kg Net: 237 kg	-67 [-33 – 100] kg CO ₂ eq. 10-30% reduction of contribution from slurry
Acidification [m ² UES, i.e. area of unprotected ecosystem]	From slurry: 43.3 m ² From fertiliser: -5.9 m ² Net: 37 m ²	From slurry: 23.0 m ² From fertiliser: -6.6 m ² Net: 16.8 m ²	-20 [-12- -28] m ² UES 30-66% reduction of contribution from slurry
N-eutrophication (aquatic) (during 10 years) [kg N - amount reaching aquatic recipients]	From slurry: 1.55 kg From fertiliser: -1.00 kg Net: 0.55 kg	From slurry: 1.55 kg From fertiliser ¹ : -1.06kg Net: 0.49 kg	-0.06 [-0.12 - 0] kg N No significant difference due to uncertainties on “avoided crop” (see text)
N-eutrophication (aquatic) (during 100 years) [kg N - amount reaching aquatic recipients]	From slurry: 1.79 kg From fertiliser: -1.11 kg Net: 0.68 kg	From slurry: 2.18 kg From fertiliser: -1.17 kg Net: 1.01 kg	0.32 [0.16 – 0.49] kg N 10-30% increase of contribution from slurry
P-eutrophication (aquatic) [kg P - amount reaching aquatic recipients]	From slurry: 0.0063 kg From fertiliser: -0.0089 kg Difference not significant due to high uncertainties	From slurry: 0.0063 kg From fertiliser: -0.0089 kg Difference not significant due to high uncertainties	No difference
Photochemical ozone formation [person.ppm.hr - see section 3.4.7]	From slurry: 0.16 p.p.h From fertiliser: -0.02 p.p.h Net: 0.14 p.p.h	From slurry: 0.09 p.p.h From fertiliser: -0.017 p.p.h Net: 0.077 p.p.h	-0.067 pers.ppm.hr [-0.033- -0.10] 20-60% reduction of contribution from slurry
Respiratory Inorganics [kg PM2.5 eq, i.e. kg equivalents of 2.5 µm size particles]	From slurry: 0.25 kg From fertiliser: - 0.05 kg Net: 0.20 kg	From slurry: 0.14 kg From fertiliser: - 0.06 kg Net: 0.08 kg	-0.11 [-0.06 – -0.17] kg PM2.5 20-70% reduction of contribution from slurry
Non-renewable energy [MJ primary energy]	From slurry: 132 MJ From fertiliser: - 410 MJ Net: -279 MJ	From slurry: 161 MJ From fertiliser ¹ : - 435 MJ Net: -275 MJ	4 [-6 – +14] MJ No significant difference
Phosphorus Resources [kg P]	From slurry: 0 kg From fertiliser: - 1.5 kg Net: - 1.5 kg	From slurry: 0 kg From fertiliser: - 1.5 kg Net: - 1.5 kg	No difference
Carbon stored in soil during 10 years [kg C]	From slurry: 11.2 kg C From fertiliser: - 4.2 kg C Net: 7.0 kg C	From slurry: 15.8 kg C From fertiliser: - 4.2 kg C Net: 11.6 kg C	4.6 [3.3 – 6.5] kg C 17.0 [12.1 – 23.8] kg CO ₂
(Corresponding to this amount of CO ₂ -eq.)	From slurry: 40.9 kg CO ₂ From fertiliser: -15.5 kg CO ₂ Net: 25.5 kg CO ₂	From slurry: 57.9 kg CO ₂ From fertiliser: -15.5 kg CO ₂ Net: 42.4 kg CO ₂	30 – 60% increase of contribution from slurry
Carbon stored in soil during 100 years [kg C]	From slurry: 3.2 kg C From fertiliser: - 1.2 kg C Net: 2.0 kg C	From slurry: 8.0 kg C From fertiliser: - 1.2 kg C Net: 6.8 kg C	4.8 [3.5 – 6.8] kg C 17.7 [12.6 – 24.8] kg CO ₂
(Corresponding to this amount of CO ₂ -eq.)	From slurry: 11.6 kg CO ₂ From fertiliser: -4.4 kg CO ₂ Net: 7.3 kg CO ₂	From slurry: 29.3 kg CO ₂ From fertiliser: -4.4 kg CO ₂ Net: 25.0 kg CO ₂	100 – 200% increase of contribution from slurry

¹This includes also the avoided N-eutrophication from the “replaced crop production”. As application of acidified slurry increase the crop production, this crop is subtracted from the system. There is a large uncertainty on this factor.

Figure 4.10. Environmental impacts for the system with acidification of slurry in an infarm NH₄⁺ plant compared to the reference system (both based on soil type JB3) – pig slurry.

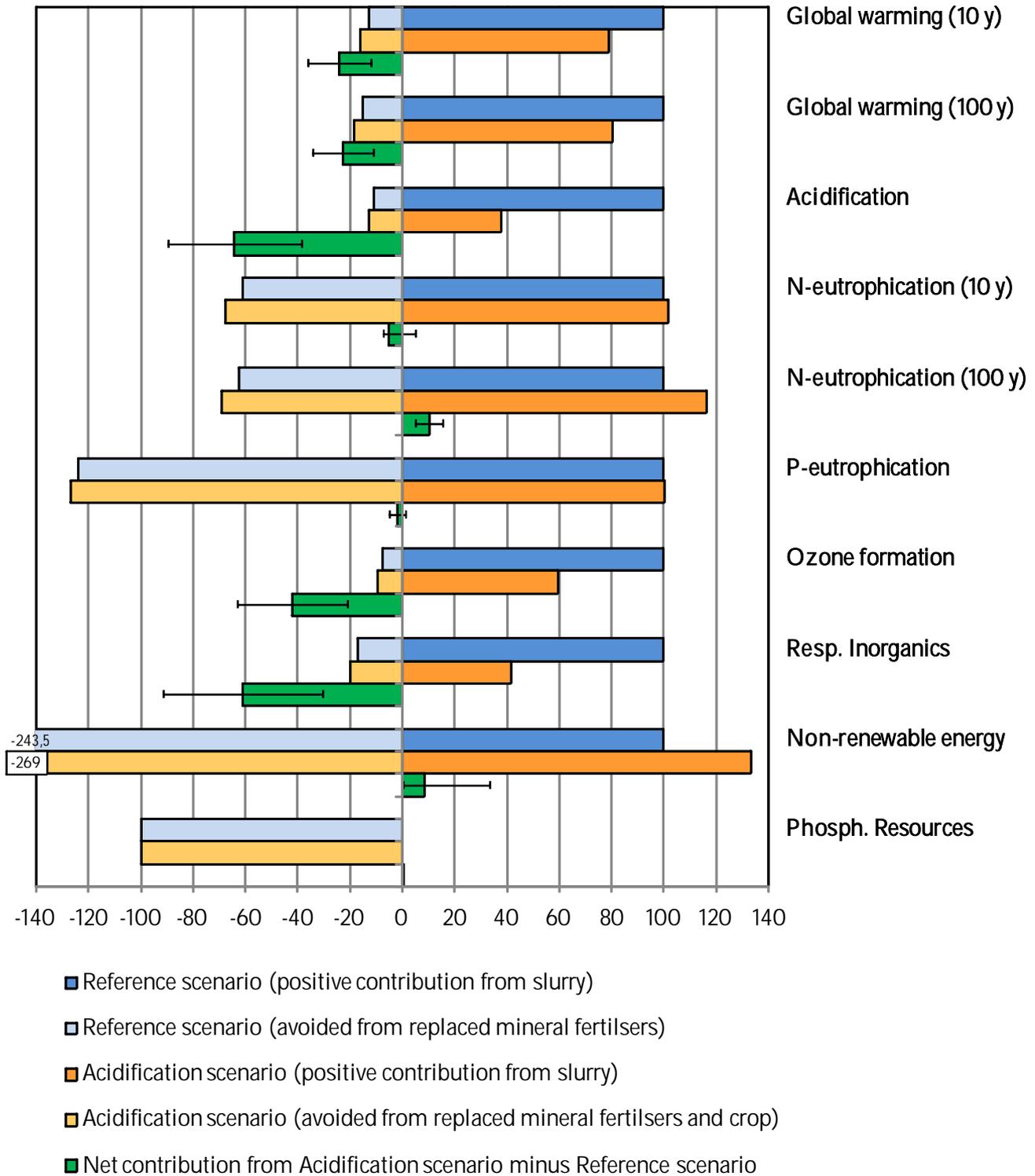
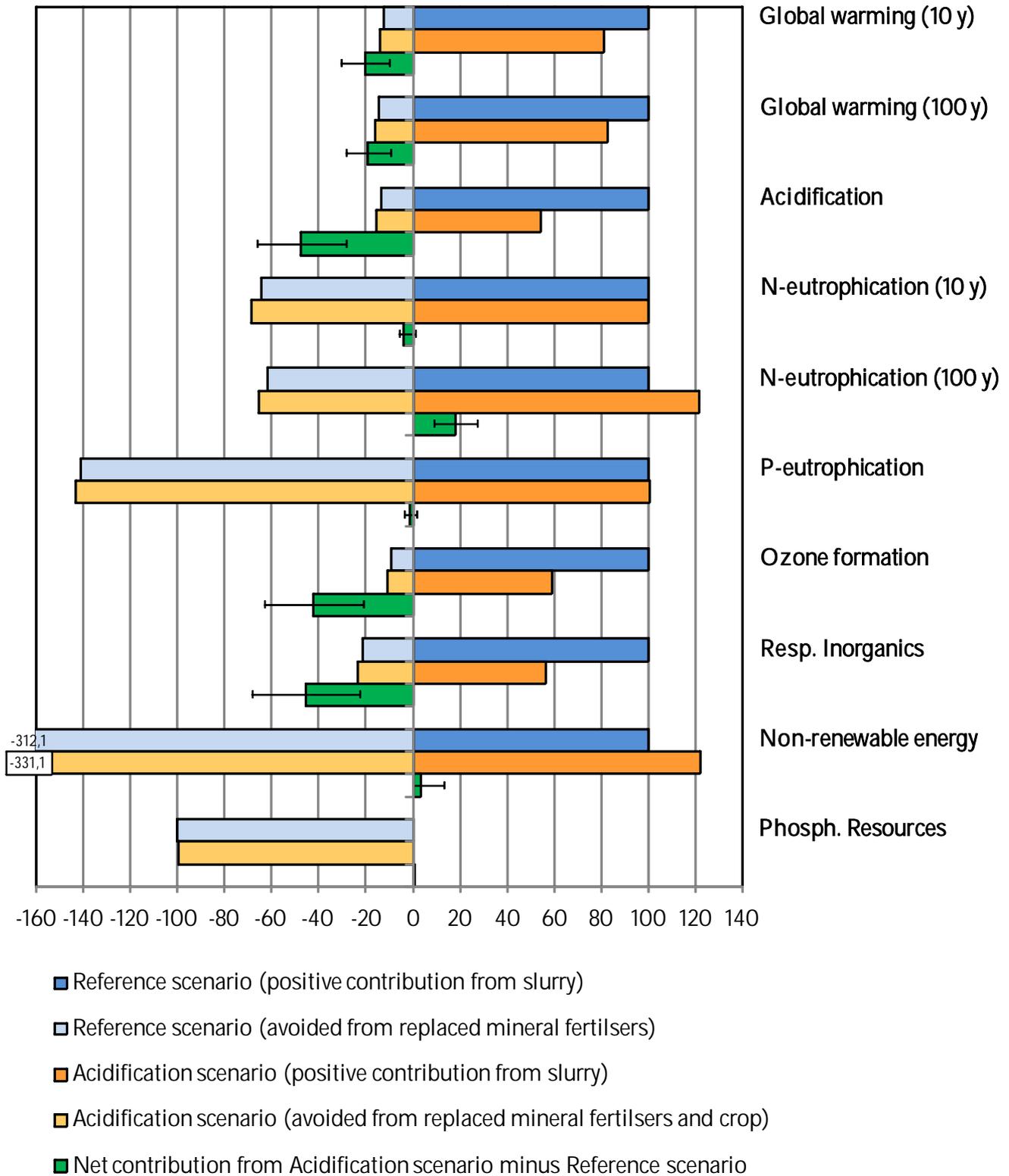


Figure 4.11. Environmental impacts for the system with acidification of slurry in an infarm NH₄⁺ plant compared to the reference system (both based on soil type JB3) – dairy cow slurry.



5 Fibre Pellets combusted in Energy Plant

This chapter contains a comparative life cycle assessment for a scenario where pig slurry is used for energy production in a Samson Bimatech Energy Plant compared with the reference scenario from chapter 3. The life cycle assessment is performed in order to answer the question: “What are the environmental benefits and disadvantages of utilising pig slurry for producing fibre pellets in a Samson Bimatech Plant MaNergy 225 and utilising the fibre pellets for heat production - compared to the reference scenario for pig slurry?”.

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

5.1 System description

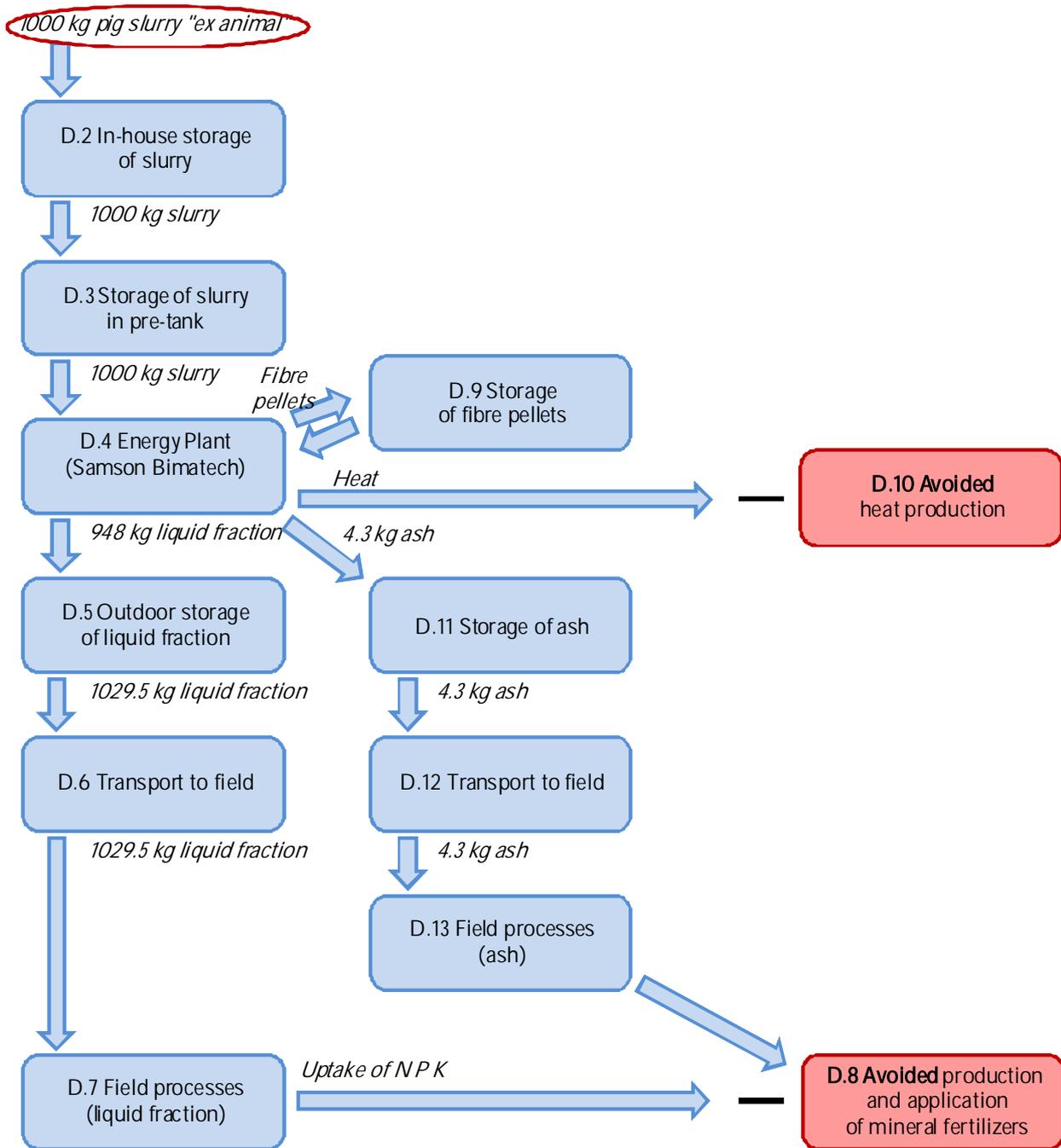
The Life Cycle Inventory Data for the Samson Bimatech Energy plant and a description of the Energy Plant and fibre pellet production can be found in Appendix C and D.

The fibre pellets are produced in a number of steps, which include mechanical separation of pig (or cattle) slurry, drying of the fibre fraction and pressing the dried fibres into pellets. The pellets can be used for heat production at the farm in a Samson Bimatech Energy Plant. The drying process of the wet fibres requires heat and this consumes approximately 40% of the energy produced by combustion of the fibre pellets. The produced heat replaces heat production by light fuel oil (or by the use of straw or wooden pellets in the sensitivity analysis) and the “replaced heat” is subtracted from the system.

The assessment includes pig slurry only, as measurement for cattle slurry was not available at the time of collecting data. Data on cattle slurry has been collected just before finalizing the project (May 2009) however, it was not possible to include this within the time frames of this study.

The scenario in this chapter contains the Energy Plant producing energy based on fibre pellets are shown in figure 5.1. The process numbers refer to the heading of the section in this Annex D and the numbers of the processes.

Figure 5.1.
Flow diagram for the scenario with the Samson Bimatech Energy Plant (Annex D).

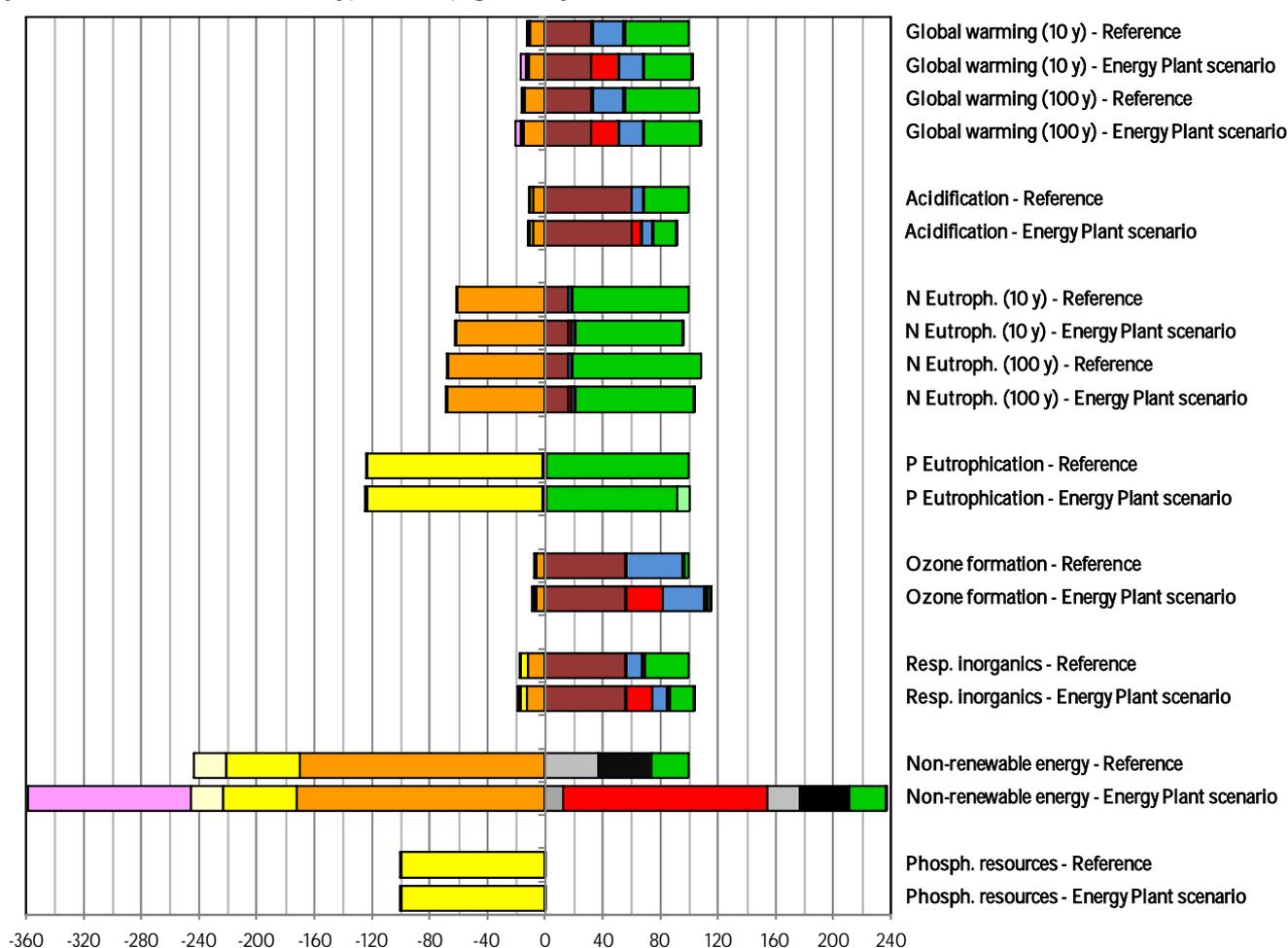


5.2 Results of the Impact Assessment

5.2.1 Overall results of the comparison

In figure 5.2, the environmental impacts from the “Samson Bimatech Energy Plant scenario” have been compared to the environmental impacts from the reference system described in chapter 3. The results are discussed in the following sections.

Figure 5.2.
Environmental impacts for the system for the Bimatech Energy Plant compared with the reference system (both based on soil type JB3) – pig slurry.



- A2 In-house storage of slurry (pig slurry)
- A3 Storage - Electricity for pumping and stirring (pig slurry)
- A4 Transport to field (pig slurry)
- A5 Field processes (pig slurry) - JB3 (10 year)
- A6 N fertiliser - production and application - JB3
- A6 P fertiliser - production and application
- A6 K fertiliser - production and application
- D2 In-house storage of slurry (pig slurry)
- D3 Electricity for storage in pre-tank
- D4 Energy plant
- D5 Storage of liquid fraction - Electricity for pumping and stirring (pig slurry)
- D6 Transport to field (liquid fraction - pig slurry)
- D7 Field processes (liquid fraction - pig slurry) - JB3 (10 year)
- D8 N fertiliser - production and application - JB3 (10 year)
- D8 P fertiliser - production and application
- D8 K fertiliser - production and application
- D9 Storage of fibre pellets
- D10 Heat production
- D11 Storage of ash
- D12 Transport to field (ash)
- D13 Field processes (ash)

5.2.2 Sensitivity analysis

Sensitivity analysis has been carried out for a number of possible variations of the Energy Plant scenario and uncertainties related to the data. Some of the results of the sensitivity analyses are shown in figures in this section, and some are described in the text under each impact category in the following sections.

In this section, the results of sensitivity analysis are shown for the difference between soil type JB3 and JB6. As can be seen from figure 5.3, the difference between soil type JB3 and JB6 has no significance for the overall conclusions.

The significance of applying a 10 years horizon or 100 year horizon is shown in figure 5.2.

As discussed in Annex C it has not been possible to find data for separating the emissions from the pre-tank from the emissions from the subsequent outdoor storage. Accordingly, the emissions are treated together under "outdoor storage". As the slurry is not separated until after the pre-tank and as the storage of the liquid fraction has lower emissions than storage of untreated slurry, the emissions from the pre-tank will be too low. A sensitivity analysis (assuming that 30% of the emissions occur from the pre-tank) indicates that the emissions from storage (pre-tank plus outdoor storage) might be at maximum 7% too low, which will not change the overall conclusions.

As mentioned in Annex C, there are significant uncertainties related to the separation indexes from the mechanical separation due to uncertainties on measurements combined with the fact that it is difficult to measure on the relatively inhomogeneous matter, slurry is. Moreover, the separation to a great degree depends on the actual slurry composition, the amount of water in the slurry, DM etc. As discussed in Annex A, the Norm Data slurry used as reference in this study, contains too low amounts of water. In real life, the concentration of the slurry has influence on the separation index. In this study, it has been necessary to keep in mind that the water content of the reference slurry is unrealistic low. The separation indexes have been used for separation of DM, N, P, K, Cu and Zn (see Annex C, table C.2) meaning that the *percentage* of DM transferred to the fibre fraction of the slurry is the same as "in real life". The fibre fraction is modelled as close to the measurements from real life as possible. It has the consequence that the liquid fraction becomes too concentrated compared to "real life measurements" as liquid fraction takes over "the lack of water" from the Norm Data.

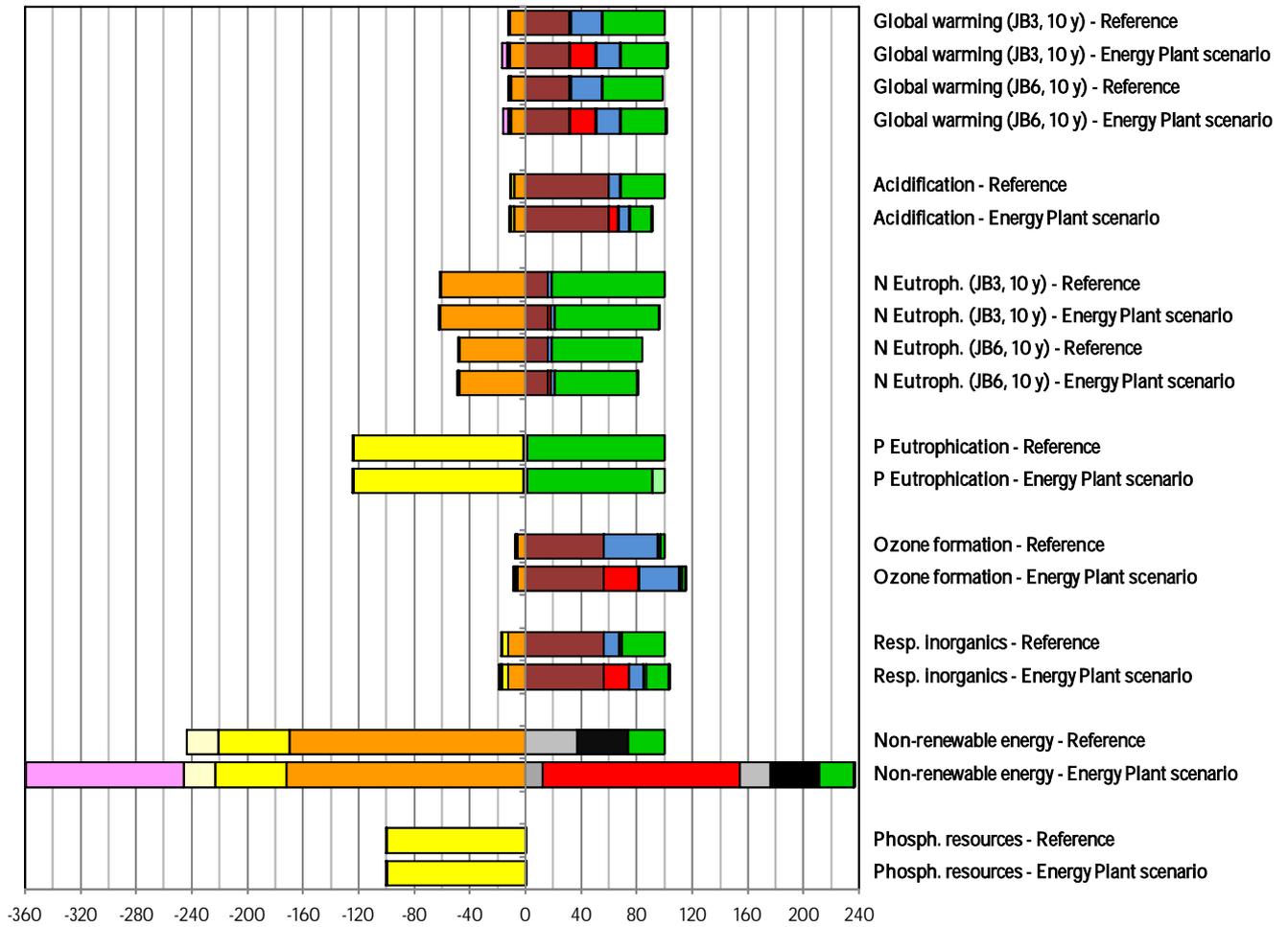
The "lack of water" in the liquid fraction has no influence on the emissions, as the emission factors are based on the actual amount of N and C rather than the concentrations of these. Adding more water to the liquid fraction (without adding more N and C) would not change the results of this study.

The results of the sensitivity analyses are discussed under each impact category in the following sections.

Figure 5.3.

Sensitivity Analysis: Difference between soil type JB3 and JB6.

Environmental impacts for the Energy Plant Scenario compared to the reference system – pig slurry.



- A2 In-house storage of slurry (pig slurry)
- A3 Storage - Electricity for pumping and stirring (pig slurry)
- A3 Storage - Emissions from storage (pig slurry)
- A4 Transport to field (pig slurry)
- A5 Field processes (pig slurry) - JB3 (10 year)
- A6 N fertiliser - production and application - JB3
- A6 P fertiliser - production and application
- A6 K fertiliser - production and application
- D2 In-house storage of slurry (pig slurry)
- D3 Electricity for storage in pre-tank
- D4 Energy plant
- D5 Storage of liquid fraction - Electricity for pumping and stirring (pig slurry)
- D6 Transport to field (liquid fraction - pig slurry)
- D7 Field processes (liquid fraction - pig slurry) - JB3 (10 year)
- D8 N fertiliser - production and application - JB3 (10 year)
- D8 P fertiliser - production and application
- D8 K fertiliser - production and application
- D9 Storage of fibre pellets
- D10 Heat production
- D11 Storage of ash
- D12 Transport to field (ash)
- D13 Field processes (ash)

5.2.3 Global warming

In figure 5.2 it can be seen that the overall contributions to global warming for the system with the Energy Plant is at the same level as the contributions from the reference system (when keeping the high uncertainty on the data in mind). The CO₂ emissions from the combustion of fibre pellets from the energy plant give a significant contribution to the global warming. This is partly counterbalanced by decreased contributions from the field processes and partly by the subtraction of “replaced heat” (to the left in figure 5.2).

The reductions from the field are attributable to the CO₂ emissions from the liquid fraction being lower than the CO₂ emissions from the untreated reference slurry in Annex A. The liquid fraction contains less C than the untreated reference slurry because a significant part of the dry matter and carbon is transferred to the fibre fraction during the mechanical separation (described in Annex C).

The energy produced by the Energy Plant replaces heat, which should have been produced by other fuels (for heating the farmer’s private house). The results in figure 5.2 are based on the assumption that the heat replaces heat production based on light fuel oil. As can be seen from figure 5.2 the CO₂ emissions from the replaced heat do not counterbalance the CO₂ emissions from the combustion of fibre pellets. This is because a significant part of the heat produced in the Energy Plant is used internally for heating and drying the fibre pellets combined with a relatively high loss of heat from the process. The “traditional oil burner” for a private house will have a higher efficiency than the Energy Plant. Changing the “replaced type of heat” change the avoided CO₂ emissions slightly but it does not change the overall conclusions.

There are no data on the CH₄ emissions from the storage of the fibre pellets. It is assumed that the biological activity is relatively low due to the low water content of the fibre pellets (normally a maximum of 10-15% water). Accordingly, it is assumed that the CH₄ emissions are relatively low compared to the CH₄ emissions from the indoor and outdoor storage. If there was significant biological activity in the fibre pellets during storage, it could increase the total contribution to global warming as the fibre pellets contain approximately 30% of the total carbon from the slurry ex animal. In that case, the “Energy Plant scenario” would have a higher contribution to global warming than the reference scenario.

5.2.4 Acidification (environmental impact)

As for the reference scenario described in chapter 3, the total contributions to acidification are mainly dominated by NH₃ emissions. Part of the contributions comes from nitrogen oxides from the Energy plant during the combustion (less than 8% of the total contributions). The scenario with the Energy Plant has reduced contributions to acidification from the field processes. This is caused by reduced NH₃ emissions from the application of the liquid fraction of the slurry. According to Hansen et al. (2008), application of the liquid fraction of slurry has an emission factor (NH₃ per total N in the slurry) that is approximately 50% of the emission factor for untreated slurry. The overall reduction of the contributions to acidification is at the level of 10% compared to the reference system, however, the actual magnitude should be interpreted with care, as the uncertainty on the nitrogen oxides from the Energy Plant is high.

As mentioned in Annex C, it has not been possible to include the NH_3 emissions during the separation process due to lack of data. For the Energy Plant, the mechanical separator is placed within the plant which uses the NH_3 emissions for the combustion process (see the description in Annex D). The plant has a constant vacuum in order to transfer emissions from the separator to the combustion chamber. Accordingly, it is likely that the NH_3 emitted to the surroundings are rather low for the Energy Plant (but not for the mechanical separator alone).

There has been no data on emissions from the storage of the fibre pellets, as described in Annex D. It is assumed that the biological activity is relatively low due to the low water content of the fibre pellets (normally a maximum of 10-15% water). As the fibre pellets contain only 15% NH_4^+ (out of the total N) it is assumed that the NH_3 emissions from the fibre pellets are insignificant. If assuming that the emission from the fibre pellets has the same emission factor as for deep litter i.e. 13% of the total N (which is a very conservative estimate, as the emissions from deep litter is most likely much higher than from fibre pellets), the NH_3 emissions for the whole system would increase with maximum 2% (due to the low amounts of fibre pellets stored per 1000 kg slurry ex animal and the low content of N in the fibre pellets). Accordingly, it is assumed that the lack of data for the storage of fibre pellets has no significance for the overall results.

5.2.5 Aquatic eutrophication (N)

As for the reference scenario, the main contributions to aquatic eutrophication (N) come from nitrate leaching (and smaller amounts from NH_3 emissions). As some of the N is removed to the fibre fraction, converted to fiber pellets and combusted, a smaller amount of N from the slurry ends at the field, which leads to a slight decrease in the contribution to aquatic eutrophication (N).

5.2.6 Aquatic eutrophication (P)

As all the phosphorous from the original reference slurry ex animal end at the field, there is no change in the contributions to aquatic eutrophication (P) (P in the fibre fraction is converted to fiber pellets, combusted and the ash is assumed to be applied to the farmer's own field, mixed with the liquid fraction).

In the steering group for the study, it has been discussed whether the ash can be used as fertiliser. According to personal communication with K. S Andersen from the Danish Environmental Protection Agency (2008) and S Sommer (2009), measurements of the ash from the Samson Bimatech Energy Plant indicate that the phosphorus in the ash is plant available. If the ash has a lower phosphorus plant availability, the reduction is limited as 9.1% of the phosphorous is transferred to the fibre fraction (see table C.2 in Annex C). Accordingly it will reduce the aquatic eutrophication (P) by maximum 9.1% if the ash is not used for fertilising or if the fertiliser value of the ash is lower. As it works now, the farmer simply mix the relatively small amounts of ash into the liquid fraction before application (4.3 kg per 1000 kg slurry).

5.2.7 Photchemical ozone formation (“smog”)

The scenario for the Energy Plant has a higher contribution to the environmental impact category “photochemical ozone formation” due to emissions of nitrogen oxides during the combustion of the fibre pellets. This is only partly counterbalanced by a slight decrease of CH₄ emissions from the outdoor storage of the liquid fraction compared to the outdoor storage of the reference slurry due to a lower content of C in the liquid fraction. There are significant uncertainties on the emissions of nitrogen oxides from the Energy Plant due to the fact that the technology is undertaking ongoing product development. With the data that have been available for this project, it must be concluded that the contribution to impact category “photochemical ozone formation” is higher for the scenario with the Energy Plant than for the reference scenario. During future product development of the Energy Plant, it could be a good idea to perform measurements for nitrogen oxides from the Energy Plant (related to the amount of slurry treated) in order to reduce the nitrogen oxide emission level.

As mentioned above, it is assumed that storage of the fibre pellets does not contribute significantly to the CH₄ emissions. If the storage of fibre pellets leads to CH₄ emissions in high amounts it could lead to even higher contributions to ozone formation. It is assumed that this is not the case.

5.2.8 Respiratory inorganics (small particles)

The contribution to the impact category “respiratory inorganics” is at the same level for the scenario with the Energy Plant as for the reference scenario (taking the uncertainties into consideration).

The Energy Plant scenario has increased contributions to respiratory inorganics caused by the emissions of nitrogen oxides (and partly by the emissions of particles). The nitrogen oxides are discussed above. However, the contributions from the field processes are lower for the Energy Plant scenario than for the reference scenario due to the reductions of NH₃ as explained above.

If the emission of nitrogen oxides from the plant is reduced significantly during the product development of the plant, there are possibilities for a net reduction of the contributions to respiratory inorganics from the scenario with the Energy Plant compared to the reference scenario.

5.2.9 Non-renewable energy resources

As can be seen in figure 5.2, the electricity consumption for the Energy Plant increases the consumption of non-renewable energy resources for the total system, compared to the reference system. However, this is partly counterbalanced by the heat produced by the Energy Plant, as it is assumed that the heat is used for the farmer’s private house, and that it replaces heat produced on light fuel oil. If the replaced fuel is not light fuel oil, but e.g. straw or wooden pellets, there is no replacement of non-renewable energy resources (as straw and wood is renewable resources), which means that there is no replacement of non-renewable energy resources. In that case, the Energy Plant scenario has a noteworthy increase of non-renewable energy resources compared to the reference scenario.

5.2.10 Consumption of phosphorus as a resource

There is no difference regarding the consumption of phosphorus as a resource between the Energy Plant scenario and the reference scenario. The phosphorus stays in the ash, and as the ash is added to the liquid fraction before application to field all the phosphorus from the slurry “ex animal” is applied to field. The handling of the ash is modelled as it is done by the farmers of the existing Energy Plants today (i.e. keeping the ash and adding it to the liquid fraction).

In the future, the farmers might be able to sell the ash as fertiliser to other farmers, transferring the phosphorus to areas with more need of phosphorus. As the mechanical separation system by Samson Bimatech separates approximately 9% of the total amount of phosphorus into the fibre fraction (see Annex C, table C.2), a future system could redistribute approximately 9% of the total phosphorus to other areas.

5.3 Conclusion

In figure 5.2 it can be seen that the overall contributions to global warming for the system with the Energy Plant is at the same level as the contributions from the reference system (when keeping the high uncertainty on the data in mind). The CO₂ emissions from the combustion of fibre pellets from the Energy Plant is partly counterbalanced by the reduced CO₂ emissions from applying the liquid fraction to field (compared to applying untreated slurry to field) and the CO₂ emissions from the replaced heat production (the Energy Plant produces heat that can be utilized for heating the farmer’s private house. The energy that would have been used for heating the farmer’s house has been subtracted from the system).

The NH₃ emissions is reduced in the Energy Plant scenario compared to the reference scenario due to reduced NH₃ emissions from the application of the liquid fraction to field compared to untreated slurry in the reference scenario. The reduced NH₃ emissions lead to a small reduction in the overall contributions to the environmental impact “Acidification”.

The contribution to aquatic eutrophication (N) is slightly reduced for the Energy Plant scenario, as a smaller total amount of N from the slurry ends at the field because some of the N is removed to the fibre fraction, converted to fiber pellets and combusted.

The contribution to aquatic eutrophication (P) is unchanged.

The scenario for the Energy Plant has a higher contribution to the environmental impact category “photochemical ozone formation” due to emissions of nitrogen oxides during the combustion of the fibre pellets. This is only partly counterbalanced by a slight decrease of CH₄ emissions from the outdoor storage of the liquid fraction compared to the outdoor storage of the reference slurry due to a lower content of C a in the liquid fraction. There are significant uncertainties on the emissions of nitrogen oxides from the Energy Plant due to the fact that the technology is undertaking ongoing product development.

The contribution to the impact category “respiratory inorganics” is at the same level for the scenario with the Energy Plant as for the reference scenario

(taking the uncertainties into consideration). The Energy Plant scenario has increased contributions to respiratory inorganics caused by the emissions of nitrogen oxides (and partly by the emissions of particles). The nitrogen oxides are discussed above. However, the contributions from the field processes are lower for the Energy Plant scenario than for the reference scenario due to the reductions of NH_3 as explained above.

The Energy Plant technology is undergoing continuous product development and the technology should be seen as being “in its child-hood”. On one hand it means that it has been difficult to obtain “high quality data” on air emissions and separation indexes. The data on air emissions has significant influence on the nitrogen oxide emissions. On the other hand it probably means that there are plenty of possibilities for improving the technology. The NO_x emissions could probably be reduced significantly by implementing known NO_x reducing technology in the Energy Plant. The separation has huge influence on the overall environmental impacts, as the main contributions come from storage and application of the liquid fraction to field – which to a great extent depend on the proportion of N and C transferred to the fibre fraction. For the mechanical separation, 29.6% of the DM and 6.8% of N is transferred to the fibre fraction (see table C.2). Increasing these separations indexes by “product development” would reduce the overall environmental performance of the system.

Table 5.1.

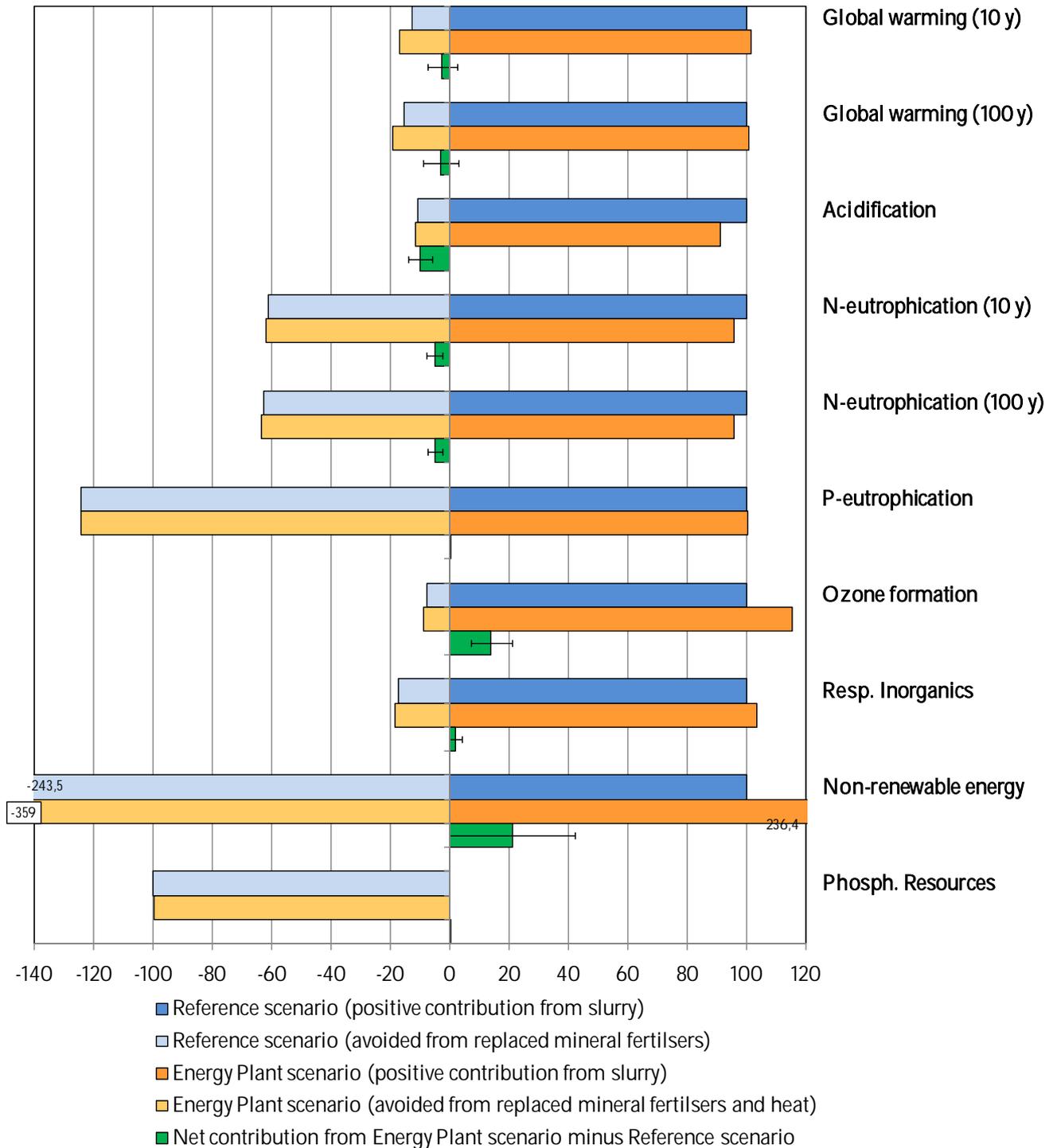
Comparison of the impacts from the Energy Plant scenario to the reference scenario for pig slurry. The number of digits is *not* an expression of the uncertainty. The uncertainty of the net contribution is based on an estimate with regard to the uncertainty on the data the forms the foundation for the LCA.

Environmental impact / resource consumption	Reference scenario	Energy Plant scenario	Net contribution i.e. "Energy Plant scenario" minus "Reference scenario"
Global warming (during 10 years) [kg CO ₂ eq.]	From slurry: 284 kg From fertiliser: -36 kg Net: 248 kg	From slurry: 289 kg From fertiliser ¹ : -48 kg Net: 241 kg	-7 [-21 – +7] kg CO ₂ eq. No significant difference
Global warming (during 100 years) [kg CO ₂ eq.]	From slurry: 304 kg From fertiliser: -47 kg Net: 257 kg	From slurry: 307 kg From fertiliser ¹ : -59 kg Net: 248 kg	-9 [-27 – +9] kg CO ₂ eq. No significant difference
Acidification [m ² UES, i.e. area of unprotected ecosystem]	From slurry: 50.3 m ² From fertiliser: -5.5 m ² Net: 44.8 m ²	From slurry: 45.7 m ² From fertiliser: -5.9 m ² Net: 39.7 m ²	-5 [-3- -7] m ² UES 6-14% reduction of contribution from slurry
N-eutrophication (aquatic) (during 10 years) [kg N - amount reaching aquatic recipients]	From slurry: 1.51 kg From fertiliser: -0.93 kg Net: 0.59 kg	From slurry: 1.44 kg From fertiliser: -0.94 kg Net: 0.51 kg	-0.08 [-0.04 - -0.12] kg N 2.5-7.7% reduction of contribution from slurry
N-eutrophication (aquatic) (during 100 years) [kg N - amount reaching aquatic recipients]	From slurry: 1.63 kg From fertiliser: -1.03 kg Net: 0.61 kg	From slurry: 1.57 kg From fertiliser: -1.04 kg Net: 0.53 kg	-0.08 [-0.04 - -0.13] kg N 2.5-7.4% reduction of contribution from slurry
P-eutrophication (aquatic) [kg P - amount reaching aquatic recipients]	From slurry: 0.0069 kg From fertiliser: -0.0086 kg Difference not significant due to high uncertainties	From slurry: 0.0069 kg From fertiliser: -0.0086 kg Difference not significant due to high uncertainties	No difference
Photochemical ozone formation [person.ppm.hr - see section 3.4.7]	From slurry: 0.18 p.p.h From fertiliser: -0.014 p.p.h Net: 0.17 p.p.h	From slurry: 0.21 p.p.h From fertiliser: -0.016 p.p.h Net: 0.19 p.p.h	0.025 pers.ppm.hr [0.012-0.038] 7-21% increase of contribution from slurry
Respiratory Inorganics [kg PM2.5 eq, i.e. kg equivalents of 2.5 µm size particles]	From slurry: 0.29 kg From fertiliser: - 0.05 kg Net: 0.24 kg	From slurry: 0.30 kg From fertiliser: - 0.06 kg Net: 0.24 kg	No significant difference
Non-renewable energy [MJ primary energy]	From slurry: 151 MJ From fertiliser: - 369 MJ Net: -217 MJ	From slurry: 358 MJ From fertiliser ¹ : - 543 MJ Net: -185 MJ	31 [0 – 200] MJ 0-130% increase of contribution from slurry ²
Phosphorus Resources [kg P]	From slurry: 0 kg From fertiliser: - 1.3 kg Net: - 1.3 kg	From slurry: 0 kg From fertiliser: - 1.3 kg Net: - 1.3 kg	No difference
Carbon stored in soil during 10 years [kg C]	From slurry: 7.5 kg C From fertiliser: - 3.9 kg C Net: 3.6 kg C	From slurry: 6.6 kg C From fertiliser: - 4.0 kg C Net: 2.6 kg C	-1.0 [-0.7 – -1.4] kg C
(Corresponding to this amount of CO ₂ -eq.)	From slurry: 27.6 kg CO ₂ From fertiliser: -14.3 kg CO ₂ Net: 13.2 kg CO ₂	From slurry: 24.2 kg CO ₂ From fertiliser: -14.5 kg CO ₂ Net: 9.7 kg CO ₂	-3.6 [-2.6 - -5.0] kg CO ₂ 9-18% decrease of contribution from slurry
Carbon stored in soil during 100 years [kg C]	From slurry: 2.1 kg C From fertiliser: - 1.1 kg C Net: 1.0 kg C	From slurry: 1.7 kg C From fertiliser: - 1.11 kg C Net: 0.6 kg C	-0.4[-0.3 – -0.6] kg C
(Corresponding to this amount of CO ₂ -eq.)	From slurry: 7.8 kg CO ₂ From fertiliser: -4.0 kg CO ₂ Net: 3.8 kg CO ₂	From slurry: 6.3 kg CO ₂ From fertiliser: -4.1 kg CO ₂ Net: 2.2 kg CO ₂	-1.6 [-1.1 - -2.2] kg CO ₂ 14-28% decrease of contribution from slurry

¹ Including replaced heat, which is especially important for non-renewable energy.

² The upper limit for the uncertainty includes the situation where the heat produced by the Energy Plant replaces renewable resources as e.g. wooden pellets or straw.

Figure 5.4.
 Environmental impacts for the Energy Plant scenario compared to the reference system (both based on soil type JB3) – pig slurry.



6 Fibre Pellets used as fertiliser

This chapter contains a life cycle assessment for a scenario where pig slurry is used for producing fibre pellets in a Samson Bimatech MaNergy 225 Energy Plant and these are used as fertiliser at the field. The “Fibre Pellets for fertilising” -scenario is compared with the reference scenario from chapter 3. The life cycle assessment is performed in order to answer the question: “What are the environmental benefits and disadvantages of utilising pig slurry for producing fibre pellets in a Samson Bimatech Energy Plant and utilising the fibre pellets for fertilising the field - compared to the reference scenario for pig slurry?”.

It should be emphasised that this scenario is mostly performed as “a test of a future possibility”, as fibre pellets are not used for fertilising today.

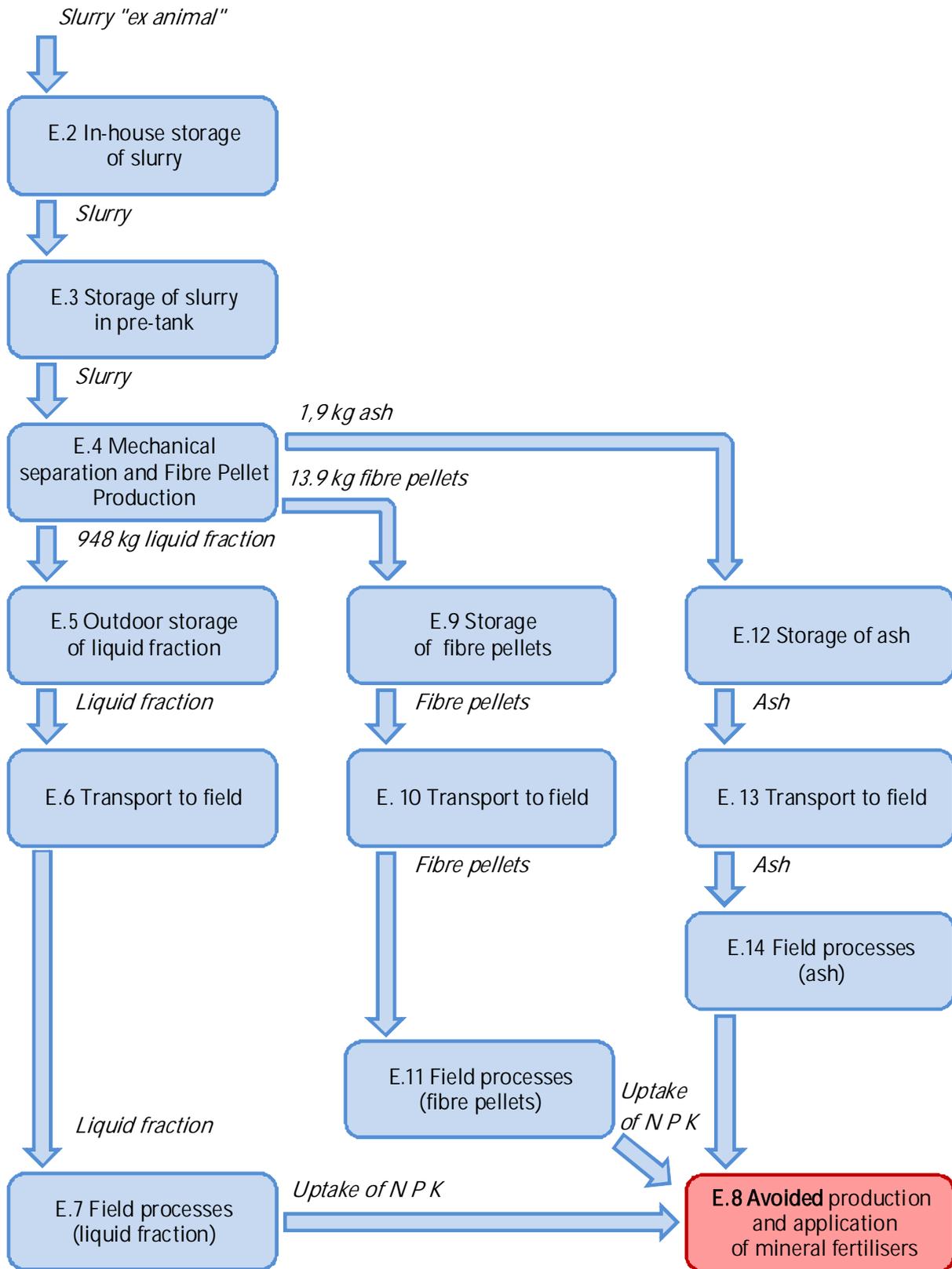
The environmental impacts and conclusions in this chapter build to a great extent on data and information delivered by the producer of the technology, Samson Bimatech and on data made for Samson Bimatech (laboratory measurements of the slurry composition). The conclusions rely on this information, and the authors do not have had the possibility of verifying the data.

6.1 System description

The system in this chapter is very alike the system in chapter 5. However, the fibre pellets are not used for heat production as in chapter 5, but for application to the field as fertiliser.

The system is shown in figure 6.1. The process numbers refer to the heading of the sections in this Annex E.

Figure E.1.
Flow diagram for the scenario with production of fibre pellets for fertilising.



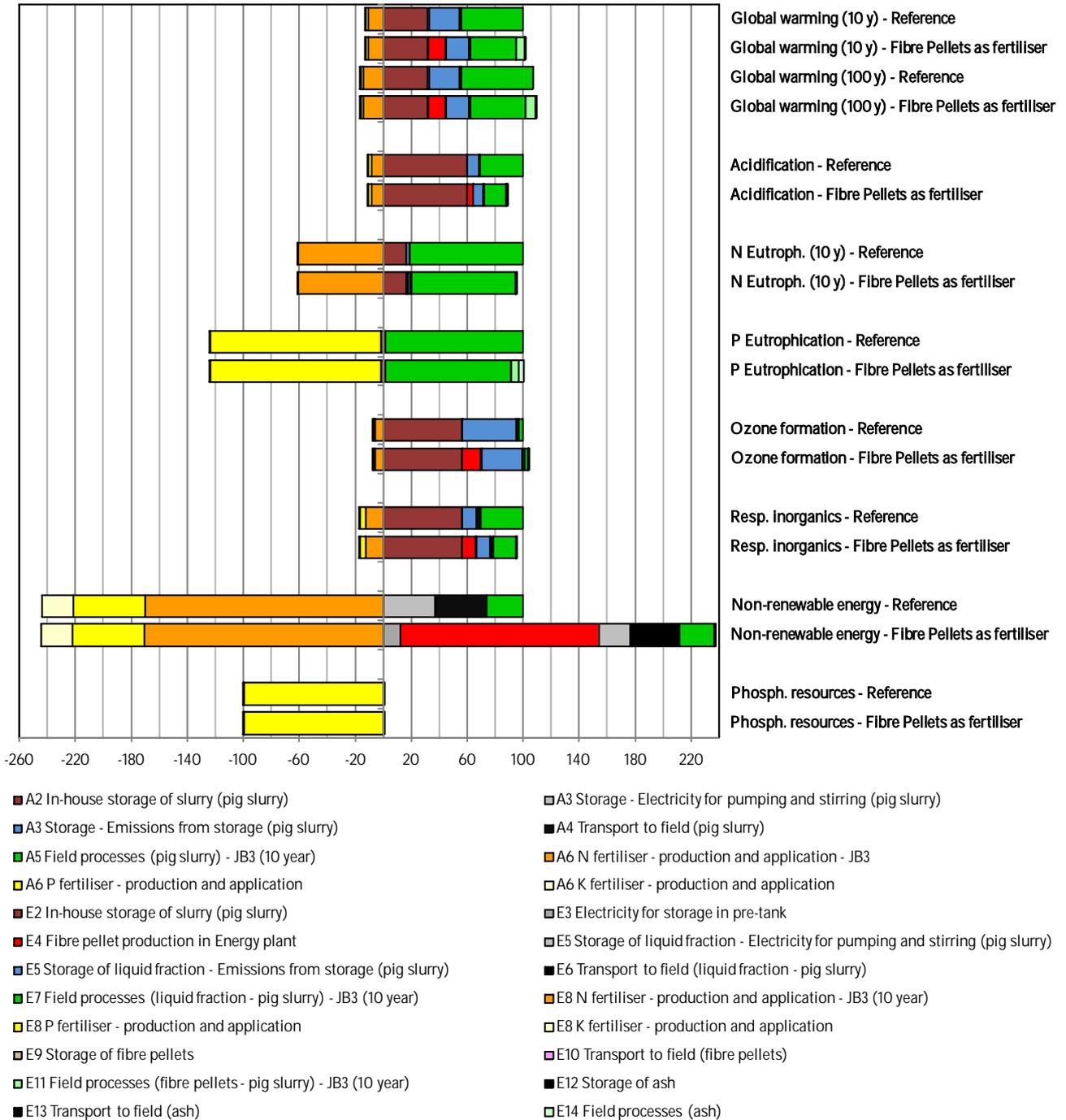
6.2 Results of the Impact Assessment

6.2.1 Overall results of the comparison

In figure 6.2, the environmental impacts from the “Fibre Pellets as fertiliser scenario” have been compared to the environmental impacts from the “reference system” described in chapter 3. The results are discussed in the following sections.

Figure 6.2.

Environmental impacts for the scenario with fibre pellets used for fertilising (fibre pellets pellets produced the Samson Bimatech Energy Plant) with the reference system (both based on soil type JB3) – pig slurry.



6.2.2 Sensitivity analysis

Sensitivity analysis has been carried out for a number of possible variations of the Energy Plant scenario and uncertainties related to the data.

In this section, the results of sensitivity analysis are shown for the difference between soil type JB3 and JB6. As can be seen from figure 6.3, the difference between soil type JB3 and JB6 has no significance for the overall conclusions.

The significance of applying a 10 years horizon or 100 year horizon is shown in figure 6.2, however only for global warming, as the 100 year leaching values cannot be calculated for N leaching.

In general, this scenario is very alike the “Energy Plant Scenario” in chapter 5, and the same uncertainties apply. Accordingly, these are not repeated here but should be read in chapter 5.

6.2.3 Global warming

The discussion regarding the contributions to global warming is generally the same as in chapter 5. The difference from chapter 5 is that only 40% of the fibre pellets are combusted, leading to a smaller contribution of CO₂ from the Energy plant (50% of the contributions from chapter 5), however, as 60% of the fibre pellets ends at the field, the CO₂ is emitted here instead (see figure 6.2). Detailed explanations can be found in Annex E. The overall conclusion is the same; there is no difference between the system for Fibre pellet production and the reference system when taking the uncertainties into consideration.

As there is no heat production (no heat surplus by the Energy Plant), replaced heat production has not been subtracted from this system.

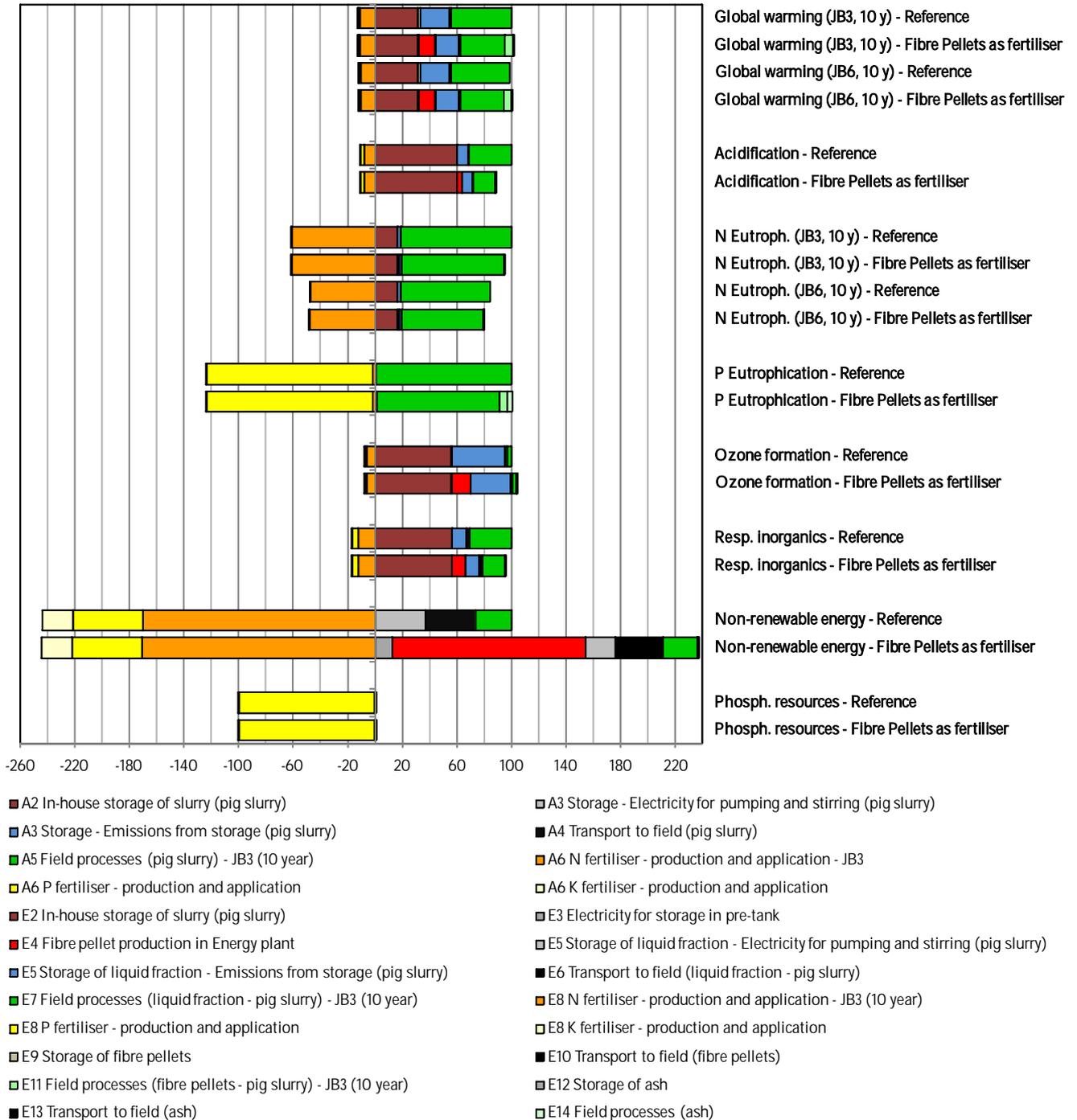
6.2.4 Acidification (environmental impact)

The conclusion regarding the acidification is generally the same as in chapter 5. The contribution from the Energy Plant is reduced by 50% due to a smaller amount of fibre pellets being combusted. However it does not change the conclusion: The scenario with the Fibre Pellet used for fertilising contributes slightly less to acidification than the reference system, due to the reduced emissions from the liquid fraction.

Figure 6.3.

Sensitivity Analysis: Difference between soil type JB3 and JB6.

Environmental impacts for the scenario with fibre pellets used for fertilising (fibre pellets pellets produced the Samson Bimatech Energy Plant) compared to the reference system – pig slurry.



6.2.5 Aquatic eutrophication (N) and (P)

The conclusions regarding aquatic eutrophication (N) is different than in chapter 5. The system with pellet production in the Energy plant contributes slightly less to the environmental impact aquatic eutrophication (N) than the reference system (due to the smaller amount of N in the liquid fraction). Furthermore, the N leaching from the fibre pellets are very low. In short, the C:N ratio of the fibre pellets is very high, which has the consequence that most of the N will be build into the humus rather than being available for crops. The fibre pellets are more suitable as “soil improvement agent” (for building up humus) than as N fertiliser. Accordingly, the net contribution to aquatic eutrophication (N) from the system with Fibre pellet production for fertilising is slightly lower than the reference system.

6.2.6 Aquatic eutrophication (P)

As all the phosphorous from the original reference slurry ex animal end at the field, there is no change in the contributions to aquatic eutrophication (P).

6.2.7 Photochemical ozone formation (“smog”)

The contribution to the impact category “photochemical ozone formation” is slightly higher for the scenario with the Energy Plant as for the reference scenario. The explanations runs parallel to the explanations in chapter 5 but the emissions from the Energy Plant itself is reduced by 50% due to a smaller amount of fibre pellets being combusted (not for the total system).

6.2.8 Respiratory inorganics (small particles)

The contribution to the impact category “respiratory inorganics” is at the same level for the scenario with the Energy Plant as for the reference scenario (taking the uncertainties into consideration). The explanations runs parallel to the explanations in chapter 5 but here the emissions from the Energy Plant is reduced by 50% due to a smaller amount of fibre pellets being combusted.

6.2.9 Non-renewable energy resources

As can be seen on figure 6.2, the consumption of non-renewable energy resources is increased considerably for the “Fibre Pellets as fertiliser”-scenario compared to the reference system. This is due to the energy consumption of the Energy Plant.

6.2.10 Consumption of phosphorus as a resource

There is no difference regarding the consumption of phosphorus as a resource between the “Fibre Pellets as fertiliser”-scenario and the reference scenario. All the phosphorus that was originally in the slurry “ex animal” is distributed to fields – by the liquid fraction, by the fibre pellets and in the ash from the combusted fibre pellets.

However, as the fibre pellets contain some of the phosphorus, and as the ash contains another part of the phosphorus, there could be future possibilities for redistributing some of the phosphorus with these two fractions. As discussed in chapter 5, approximately 9% of the phosphorus is transferred to the fibre fraction and from this to the fibre pellets (60%) and to the ash (40%).

The modelling of the fate of this phosphorus if redistributed to other fields with more need for phosphorus has been above the time and budget of this project. However, it is recommended to include aspects of this in a future project.

6.3 Conclusion

The results of the comparison are shown in table 6.1 and figure 6.4 below.

When keeping the overall uncertainty on the data in mind, there is no significant difference between the overall contributions to global warming, aquatic eutrophication (P), “respiratory inorganics” and the consumption of phosphorus as a resource when comparing the “Fibre Pellets used for fertilising”-scenario compared to the reference system.

The “Fibre Pellets used for fertilising”-scenario has a slightly reduced contribution to the environmental impact “Acidification” and to aquatic eutrophication (N) than the reference system due to the reduced NH_3 emissions and N leaching from the liquid fraction applied to field compared to untreated slurry.

The contribution to “photochemical ozone formation” is slightly higher from the “Fibre Pellets used for fertilising”-scenario compared to the reference system.

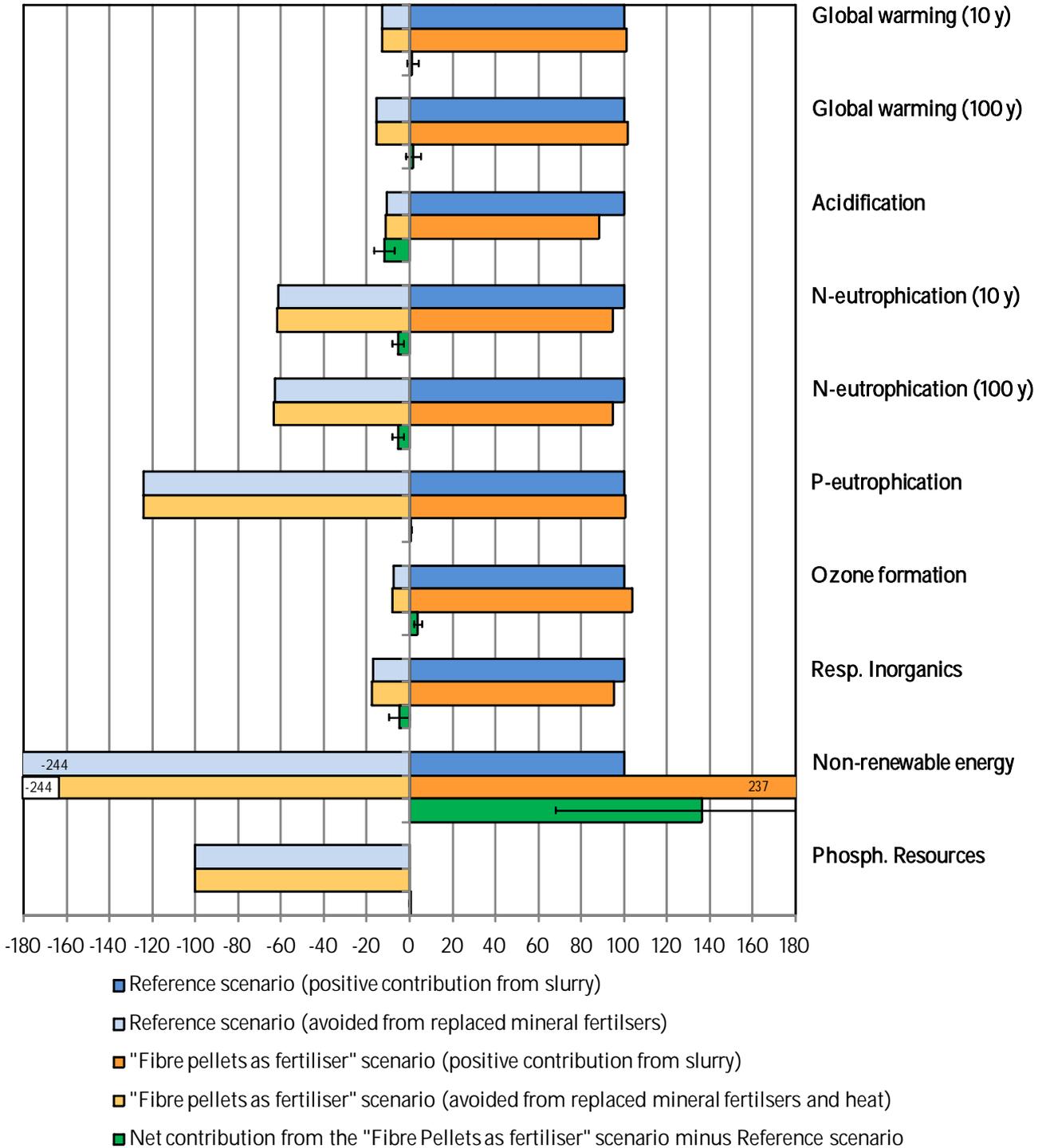
The consumption of non-renewable energy resources is considerably higher caused by the electricity consumption by the Energy Plant.

Table 6.1.

Comparison of the impacts from the scenario with fibre pellets used for fertilising (fibre pellets produced the Samson Bimatech Energy Plant) to the reference scenario for pig slurry. The number of digits is *not* an expression of the uncertainty. The uncertainty of the net contribution is based on an estimate with regard to the uncertainty on the data the forms the foundation for the LCA.

Environmental Impact / resource consumption	Reference scenario	"Fibre Pellets as fertiliser" scenario	Net contribution i.e. "Fibre Pellets as fertiliser scenario" minus "Reference scenario"
Global warming (during 10 years) [kg CO ₂ eq.]	From slurry: 284 kg From fertiliser: -36 kg Net: 248 kg	From slurry: 288 kg From fertiliser: -36 kg Net: 252 kg	4 [-4 – +11 kg CO ₂ eq. No significant difference
Global warming (during 100 years) [kg CO ₂ eq.]	From slurry: 304 kg From fertiliser: -47 kg Net: 257 kg	From slurry: 310 kg From fertiliser: -47 kg Net: 263 kg	5 [-5 – +16] kg CO ₂ eq. No significant difference
Acidification [m ² UES, i.e. area of unprotected ecosystem]	From slurry: 50.3 m ² From fertiliser: -5.5 m ² Net: 44.8 m ²	From slurry: 44.4 m ² From fertiliser: -5.5 m ² Net: 38.9 m ²	-5.9 [-3.5- -8.3] m ² UES 7-16% reduction of contribution from slurry
N-eutrophication (aquatic) (during 10 years) [kg N - amount reaching aquatic recipients]	From slurry: 1.51 kg From fertiliser: -0.93 kg Net: 0.59 kg	From slurry: 1.43 kg From fertiliser: -0.93 kg Net: 0.50 kg	-0.08 [-0.042 - -0.13] kg N 2.7-8.0% reduction of contribution from slurry
N-eutrophication (aquatic) (during 100 years) [kg N - amount reaching aquatic recipients]	From slurry: 1.63 kg From fertiliser: -1.03 kg Net: 0.61 kg	Could not be modelled	Could not be modelled
P-eutrophication (aquatic) [kg P - amount reaching aquatic recipients]	From slurry: 0.0069 kg From fertiliser: -0.0086 kg No significant difference	From slurry: 0.0069 kg From fertiliser: -0.0086 kg No significant difference	No difference
Photochemical ozone formation [person.ppm.hr - see section 3.4.7]	From slurry: 0.18 p.p.h From fertiliser: -0.014 p.p.h Net: 0.17 p.p.h	From slurry: 0.19 p.p.h From fertiliser: -0.014 p.p.h Net: 0.17 p.p.h	0.007 pers.ppm.hr [0.003-0.009] 2-5% increase of contribution from slurry
Respiratory Inorganics [kg PM2.5 eq, i.e. kg equivalents of 2.5 µm size particles]	From slurry: 0.29 kg From fertiliser: - 0.05 kg Net: 0.24 kg	From slurry: 0.27 kg From fertiliser: - 0.05 kg Net: 0.22 kg	No significant difference
Non-renewable energy [MJ primary energy]	From slurry: 151 MJ From fertiliser: - 369 MJ Net: -217 MJ	From slurry: 359 MJ From fertiliser: - 370 MJ Net: -11 MJ	200 [100 – 300] MJ 70-200% increase of contribution from slurry
Phosphorus Resources [kg P]	From slurry: 0 kg From fertiliser: - 1.3 kg Net: - 1.3 kg	From slurry: 0 kg From fertiliser: - 1.3 kg Net: - 1.3 kg	No difference
Carbon stored in soil during 10 years [kg C]	From slurry: 7.5 kg C From fertiliser: - 3.9 kg C Net: 3.6 kg C	From slurry: 8.0 kg C From fertiliser: - 3.9 kg C Net: 4.1 kg C	0.5 [0.3 – 0.6] kg C 1.7 [1.2 – 2.3] kg CO ₂
(Corresponding to this amount of CO ₂ -eq.)	From slurry: 27.6 kg CO ₂ From fertiliser: -14.3 kg CO ₂ Net: 13.2 kg CO ₂	From slurry: 29.3 kg CO ₂ From fertil.: -14.4 kg CO ₂ Net: 14.9 kg CO ₂	4-8% increase of contribution from slurry
Carbon stored in soil during 100 years [kg C]	From slurry: 2.1 kg C From fertiliser: - 1.1 kg C Net: 1.0 kg C	From slurry: 2.1 kg C From fertiliser: - 1.11 kg C Net: 1.9 kg C	-0.02 [-0.01 – -0.03] kg C -0.08 [-0.06 - -0.11] kg CO ₂
(Corresponding to this amount of CO ₂ -eq.)	From slurry: 7.8 kg CO ₂ From fertiliser: -4.0 kg CO ₂ Net: 3.8 kg CO ₂	From slurry: 7.8 kg CO ₂ From fertiliser: -4.1 kg CO ₂ Net: 3.7 kg CO ₂	0.7-1.4% decrease of contribution from slurry

Figure 6.4.
 Environmental impacts for the scenario with fibre pellets used for fertilising (fibre pellets produced the Samson Bimatech Energy Plant) compared to the reference system (both based on soil type JB3) – pig slurry.



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Annex A. Reference Scenarios – Life Cycle Inventory data

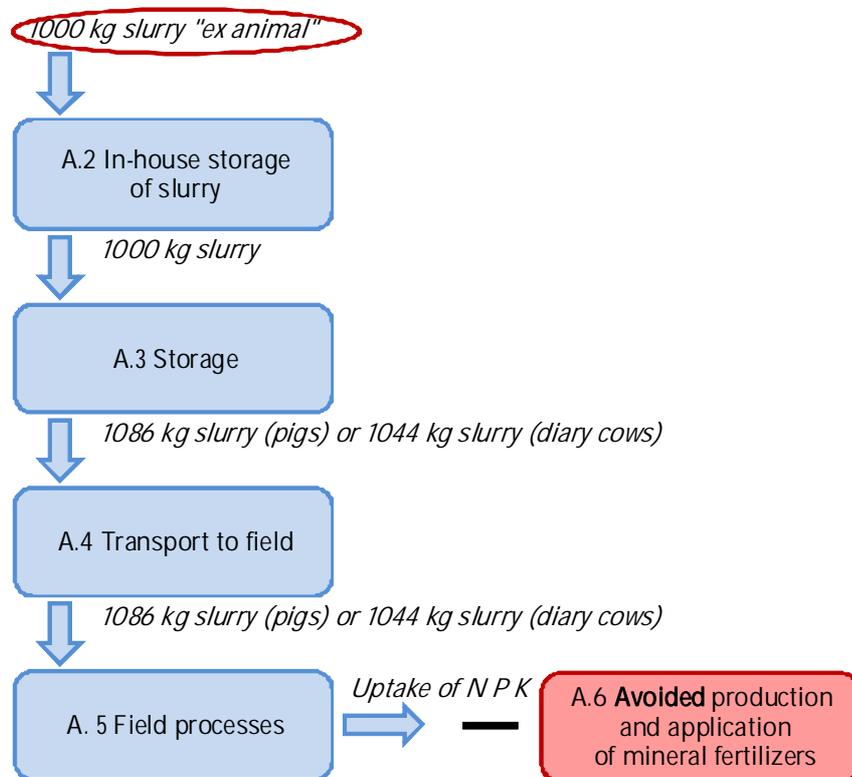
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A.1 System Description and composition of reference slurry

A.1.1 System description

The overall system for the reference scenario is described in section 3.1 of the report. The overall system description will not be repeated here. In addition to the system described in section 3.1, pumping and stirring have been included (i.e. pumping of slurry from the pre-tank to the outdoor storage, pumping from the outdoor storage to the transport tank before application to field and stirring of the slurry in the pre-tank and in the outdoor storage tank). See the flow diagram in figure A.1. The numbers in the figure refer to the numbers of the section in this Annex.

Figure A.1.
Flow diagram for the reference scenario.



A.1.2 Composition of the reference slurry

The characteristics of the “reference slurry” for fattening pigs in the reference scenario are shown in table A.1 (per 1000 kg of slurry). The characteristics of the “reference slurry” for dairy cows are shown in table A.2 (per 1000 kg of slurry). The characteristics are given “ex animal”, “ex housing” and “ex storage”, see figure 3.2 in chapter 3. The references, assumptions and calculations are explained in the sections below.

Table A.1.
Characteristics of slurry from fattening pigs in the reference scenario.
Per 1000 kg of slurry “ex animal”, “ex housing” and “ex storage”.

	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 ^a
Volatile solids (VS)	64.2 kg	56.5 kg	48.8 kg ^b
Of total VS:			
- easily degradable	41.7 kg	34.0 kg	28.1 kg
- heavy degradable	22.5 kg	22.5 kg	20.7 kg
<i>Total-N (DJF, 2008)</i>	<i>6.60 kg</i>	<i>No data (calculated: 5.54 kg)</i>	<i>5.00 kg</i>
Total-N in this study	6.60 kg	5.48 kg	4.80 kg
NH ₄ ⁺ -N	No data	No data	3.60 kg ^c
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

^a Ash “ex storage” = 20% of DM

^b VS “ex storage” = 80% of DM

^c For pig slurry, the content of NH₄⁺-N ex storage corresponds to 75% of the total N content (Poulsen et al. (2001) and DJF (2008b))

Table A.2.
 Characteristics of slurry from dairy cows in the reference scenario.
 Per 1000 kg of slurry "ex animal", "ex housing" and "ex storage".

	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 ^a
Volatile solids (VS)	104.2 kg	91.7 kg	82.4 kg ^b
Of total VS:			
- easily degradable	50.0 kg	37.5 kg	30.5 kg
- heavy degradable	54.2 kg	54.2 kg	51.9 kg
<i>Total-N (DJF, 2008)</i>	<i>6.87 kg</i>	<i>No data (calculated: 6.41 kg)</i>	<i>6.02 kg</i>
Total-N in this study	6.87 kg	6.34 kg	5.79 kg
NH ₄ ⁺ -N	No data	No data	3.47 kg ^c
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 kg	12.1 kg	11.6 g
Zinc (Zn)	23.4 kg	23.4 kg	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

^a Ash "ex storage" = 20% of DM

^b VS "ex storage" = 80% of DM

^c For cattle slurry, the content of NH₄⁺-N ex storage corresponds to 60% of the total N content (Poulsen et al. (2001) and DJF (2008b))

The data for dry matter (DM), nitrogen (N), phosphorus (P) and potassium (K) are based on the Danish Normative system for assessing manure composition (Poulsen et al. (2001), DJF (2008a) and DJF (2008b)). It is however acknowledge that these values might differ notably from the composition of pig and cattle slurry measurements "in the real world" due to differences in e.g. diets and slurry handling. Therefore, the "ex storage" values from the Danish Normative system have been compared to measurements from Knudsen and Birkmose (2005) and Hansen et al. (2008), as shown in table A.3. The "ex storage" values are the values compared since this is what was available in the literature for comparison. The measurements by Knudsen and Birkmose (2005) are based on 55 samples of pig slurry and 50 samples of cattle slurry. According to Birkmose (2008, personal communication), the pig slurry samples are from all kind of pig farms (including mixed farms with sows, piglets and fattening pigs). The cattle samples are primarily based on dairy farms, but for these, calves are often included. In their study, the storage time and method for the slurry varies. As it can be seen from table A.3, there are considerable variations on the minimum and maximum for the measurements. The data in Hansen et al. (2008) are based on more than 270 samples of pig slurry and 200 samples of cattle slurry. The measurements were made right before the application to field (Personal communication, Hansen, 2009).

Table A.3.

Values from DJF (2008a) compared to measurements (Knudsen and Birkmose, 2005) and Hansen et al. (2008) for selected characteristics of pig and cattle slurry. Uncertainty range appears in brackets []. All data are given in kg per 1000 kg slurry ex storage.

Reference	Pigs				Cattle		
	DJF (2008a)	Knudsen and Birkmose (2005)	Hansen et al. (2008)	Hansen et al. (2008)	DJF (2008a)	Knudsen and Birkmose (2005)	Hansen et al. (2008)
	Fattening pigs	Pigs	Fattening Pigs	Pigs	Dairy cows	Cattle	Cattle
Dry matter (DM)	61	38 [11-100]	41.0	43.1	103	64 [14-110]	74.1
Total-N	5.00	4.2 [1.8-8.2]	4.14	4.24	6.02	3.2 [1.2-5.8]	3.65
NH ₄ -N	3.75	3.5 [1.6-6.7]	3.25	3.34	3.61	2.0 [1.0-3.2]	2.12
Total-P	1.04	0.8 [0.2-2.2]			0.98	0.6 [0.2-0.9]	
Potassium (K)	2.60	2.4 [1.0-4.8]			5.65	2.8 [1.2-4.2]	

From table A.3, it can be seen that the concentrations for fattening pig slurry from the Danish Normative system in general is higher than the “average pig farms” measured by Knudsen and Birkmose (2005) and Hansen et al. (2008). This is probably due to the fact that Knudsen and Birkmose (2005) includes all kind of pig farms and mixed farms including sows and piglets and, again, differences in feeding, housing systems, slurry handling, slurry storage time etc. Furthermore, the Danish Normative system does not include water added in the housing systems, as described below. Thus, the concentrations “ex storage” are higher as the slurry is less diluted.

The dairy cow slurry from the Danish Normative system has a significant higher content of dry matter and a higher concentration of nitrogen (N), phosphorous (P) and potassium (K) than the measurements made by Knudsen and Birkmose (2005) and Hansen et al. (2008). Actually, all the DJF (2008) values for dairy cows are higher than the upper limit of the uncertainty range provided by Knudsen and Birkmose (2005). Knudsen and Birkmose (2005) suggest that the difference between the measured data and the data from the Danish Normative system is probably due to the fact that more water is actually added (in the housing systems or during outdoor storage) than what is included in the Norm data. Poulsen et al. (2001) do not include added and lost water in the housing systems in their calculations. They estimate the values in tables, but do not include these values in the calculations. The same problem appears in the data from DJF (2008a). Poulsen et al. (2001, page 96) state that due to lack of data, the loss of water and evaporation of water is not included in the calculations and instead of calculating dry matter it is set in accordance with measurements from “real life”.

It has not been possible to perform sensitivity analysis for variations of slurry compositions, as the slurry composition influences on all mass balances and all emissions throughout the report and in all Annexes. This would require a

modelling tool, which has not been established within the frames of the budget.

There are also unexplained deviations in the mass balances in the DJF (2008a) data for the outdoor storage (added rain) (see table A.4 below). Jacobsen et al. (2002) state that the method used by Poulsen et al. (2001) is problematic as the amount of slurry ("ex animal") and inputs and outputs from the housing system and during the storage do not necessarily yield the amount "ex storage" that is given in the Norm Data. The problem appears for all years, also data in DJF (2008a). Jacobsen et al. (2002, table 2.5) calculated the mass balances and found deviations ranging between -77% to +32%.

In table A.4 the mass balances used in DJF (2008a) are shown. Furthermore, mass balances when including water added in the housing system are shown. The amount of added water is based on data from Poulsen et al. (2001). However, the mass balances for including water in the housing systems give too high amount of water as there is no data for the evaporation.

When regarding table A.4 it seems that the mass balances by DJF (2008a) include inadequate amounts of water, especially for dairy cow slurry, and it is likely that this is part of the reason for the difference between the Norm Data and the measurements as shown in table A.3.

As described in chapter 3, it is assumed that the slurry tank for outdoor storage is covered by a floating layer of straw (pig slurry) or a natural floating layer (cattle slurry). These covers do not prevent rain from diluting the slurry. According to Poulsen et al. (2001, page 128) the amount corresponds to approximately 110 litres of water per 1000 kg slurry "ex housing". However, when using the Norm Data for 2008 (DJF, 2008), the amount of water applied is significantly lower for dairy cows (4.4% as can be seen from table A.4).

In spite of this, it has been ***chosen to use the Norm Data without corrections*** for the water amounts in this study, as the Norm Data are "Danish standard data" used for the majority of the Danish slurry studies and as it is not within the frames of this report to improve the Danish Norm Data nor to claim a better knowledge of slurry composition.

Table A.4.

Mass balances for the total volume of slurry “ex animal”, “ex housing” and “ex storage” used in this study and from DJF (2008a).

	Ex animal	Water added in the housing system	Ex housing	Net amount of rain added during storage	Ex storage	Relative increase in pct. i.e. (Ex storage – ex animal) / Ex animal
Fattening pigs (fully slatted floor)						
DJF (2008a)	0.47 tonnes	Not included	Not stated	Included amount not documented	0.52 tonnes	$\frac{(0.52-0.47)}{0.47}$ = approx. 10% (actually 8.6%) ^a
Mass balances made on the basis of data from Poulsen et al. (2001).	1000 kg	223 kg ^b	1223 kg	135 kg ^c	1358 kg	$\frac{(1358-1000)}{1000}$ = 36%
This study (based on DJF (2008a))	1000 kg	Not included	1000 kg	+ 8.6% ^a	1086 kg	$\frac{(1086-1000)}{1000}$ = approx. 8.6% ^a
Dairy cows (Cubicle housing system, slatted floor, channel)						
DJF (2008a)	20.4 tonnes	Not included	Not stated	Included amount not documented	21.3 tonnes	$\frac{(21.3-20.4)}{20.4}$ = 4.4%
Mass balances made on the basis of data from Poulsen et al. (2001).	1000 kg	152 kg ^d	1152 kg	127 kg ^c	1279 kg	$\frac{(1279-1000)}{1000}$ = 28%
This study (based on DJF (2008a))	1000 kg	Not included	1000 kg	+ 4.4%	1044 kg	$\frac{(1044-1000)}{1000}$ = 4.4%

^a The data in DJF (2008a) is rounded off (e.g. 0.47 instead of 0.474). When using the rounded data for the calculations, the “ex storage” values are not exactly the same as in DJF (2008a). The dilution factor that fits best with the “ex storage” data is that 8.6% water is added.

^b For fattening pigs (at fully slatted floors), the amount of wasted drinking water is estimated to 75 liters per pig and cleaning water to 30 litres per pig (DJF (2008b) and Poulsen et al. (2001)). As one pig produces 0.47 tonnes of slurry (DJF (2008a)), the water wasted in the housing system corresponds to 105 litres/0.47 tonnes = 223 kg per 1000 kg.

^c The net amount of rain (i.e. rain minus evaporation) is 110 kg per 1000 kg slurry “ex housing” (Poulsen et al. (2001, page 128-130) and DJF (2008b)).

^d For dairy cows, slurry based housing unit, the amount of wasted drinking water is estimated to 100 litres per cow per year and cleaning water to 3000 litres per cow per year (DJF, 2008b, and Poulsen et al., 2001). As one cow produces 20.4 tonnes of slurry per year (DJF, 2008a), the water wasted in the housing system corresponds to 3100 litres/20.4 tonnes = 152 kg per 1000 kg slurry.

A.1.3 Mass balances for N, P and K

In the Danish Normative system for assessing manure composition, the data for nitrogen (N), phosphorus (P) and potassium (K) are given “ex animal” and “ex storage”. This study is based on the “ex animal” and “ex storage” values from DJF (2008a). The “ex housing” values are calculated by establishing mass balances from “ex animal” to “ex housing system” and from this to “ex storage” following the natural flow of the slurry:



The calculations for N, P and K are shown in table A.5 for fattening pig slurry and in table A.6 for dairy cow slurry. The explanations are given in the text and in the notes for the tables.

The Total-N in the slurry “ex animal” and “ex storage” is based on data from DJF (2008a).

The total-N in the slurry “ex housing” is calculated in accordance with the preconditions in Poulsen et al. (2001). For fattening pigs in housing units with fully slatted floors, the in-housing NH_3 emission corresponds to 16% (NH_3 -N in pct. of the total N ex animal). For dairy cows in cubicle housing systems with slatted floor (1.2 m channel) the emission factor is 8% (NH_3 -N in pct. of the total N ex animal). The NH_3 -emissions during storage of slurry correspond to 2% (NH_3 -N in pct. of the total-N ex housing) for both pig slurry and cattle slurry. In DJF (2008b), new preconditions are given for the NH_3 emissions, however, when calculating the N balances for fattening pigs and dairy cows in DJF (2008a), it seems that the new preconditions from DJF (2008b) have not been used. Accordingly, the preconditions from Poulsen et al. (2001) have been used in this report.

As mentioned in section 3.2, the NH_4^+ -N in the slurry “ex housing” and “ex animal” has not been estimated in this report, as data on this has not been identified and as balances on NH_4^+ could not be established. As there are microbial metabolisms and biochemical processes transforming organic N to inorganic N it is not reasonable to assume that the relative amount of NH_4^+ -N “ex housing” and “ex animal” is the same as “ex storage”.

In the housing units for dairy cows, straw is added as bedding material. According to Poulsen et al. (2001) the amount is 1.2 kg per animal per day for slurry based housing units for dairy cows. Adding of straw affects the mass balances for nitrogen, phosphorous, and potassium, see table A.6.

According to Poulsen et al. (2001) and DJF (2008b), straw is not added to fattening pigs in fully slatted floor housing systems.

For pig slurry, straw is added as a floating layer during storage in order to reduce the emissions, as described in chapter 3. It is assumed that straw is not added to slurry tanks for dairy cows. Cut straw is added as floating layer to cover pig slurry during storage corresponds to 10 kg straw per m^2 slurry surface (Rasmussen et al., 2001). With a 4 m deep slurry tank this corresponds to 2.5 kg straw per 1000 kg slurry. The added straw increases

the total mass slightly (2.5 kg per 1000 kg). The added mass of the straw is less than 0.3% of the total mass ¹. This is insignificant for the overall results and the inclusion would reduce the transparency of the calculations more than it would increase the precision of the results. The amounts added by the straw are insignificant compared to the differences between the compositions of slurry from farm to farm. For dry matter, the added amount corresponds to 3.4% ², which is regarded as insignificant compared to the overall uncertainty.

The amount of N, P and K added in the straw for the floating layer for outdoor storage of pig slurry is insignificant. ³ Accordingly, the mass, dry matter, nitrogen, phosphorus and potassium added by the straw during outdoor storage have been ignored in this study. Added straw during outdoor storage is not included in the mass balances in DJF (2008) either.

Phosphor (Total-P) and potassium (K) “ex animal” and “ex storage” are based on DJF (2008a). For dairy cows slurry, P and K is added by the added straw in the housing system. The amount of Total P and K is assumed to be unchanged during outdoor storage.

¹ The amount of straw corresponds to 2.5 kg (10 kg straw per m² slurry surface (Rasmussen et al. (2001). With a 4 m deep slurry tank this corresponds to 2.5 kg straw per 1000 kg slurry. $2.5 \text{ kg straw per } 1000 \text{ kg slurry} = 0.25\%$

² DM in straw: 85% (Poulsen et al., 2001, page 89). Total added amount of dry matter: $2.5 \text{ kg} * 0.85 = 2.1 \text{ kg}$. This corresponds to 3.4% of the total amount (61 kg in 1000 kg slurry).

³ As mentioned above, 2.5 kg straw is added to pig slurry during storage. According to Poulsen et al., 2001, page 89, straw contains 85% dry matter (DM). Straw contains 0.005 kg N per kg DM in straw:
N added in straw = $0.005 \text{ kg N per kg DM} * 0.85 * 2.5 \text{ kg} = 0.01 \text{ kg N}$ (0.2% of the content of N in slurry “ex storage”).
Straw contains 0.00068 kg P per kg DM
P added in straw = $0.00068 \text{ kg P per kg DM} * 0.85 * 2.5 \text{ kg} = 0.0015 \text{ kg P}$ (0.1% of the content of P in slurry “ex storage”).
Straw contains 0.01475 K kg per kg DM per 1000 kg slurry.
K in straw = $0.01475 \text{ kg K per kg DM} * 0.85 * 2.5 \text{ kg} = 0.031 \text{ kg K}$ (1% of the content of K in slurry “ex storage”).

Table A.5.

Calculation of the "ex housing" characteristics of slurry from fattening pigs (reference scenario)

	Ex animal	Mass balances and calculations				Ex housing	Ex storage
		In-housing change	Ex housing total (C) = (A)+(B)	Change during storage (D) (based on Poulsen et al., 2001)	Ex storage total (E) = (C)+(D)		
	(A) (based on DJF (2008a))	(B) (based on Poulsen et al., 2001)				(F) = (C) * 1000 kg/ 1000 kg ^a	(G) = (E) * 1000 kg/ 1086 kg ^a
Total mass	1000 kg Slurry ex animal	Not included ^a	1000 kg	+86 kg ^a	1086 kg	1000 kg Slurry ex housing	1000 kg Slurry ex storage
Total-N according to DJF, 2008a)	6.60 kg ^b	-1.06 kg ^c	5.54 kg	-0.11 kg ^d	5.43 kg	5.54 kg	5.00 kg
Used in this study: Total-N when including emissions of N ₂ O, NO and N ₂	6.60 kg ^b	-1.06 kg ^c -0.013 kg ⁱ -0.013 kg -0.039 kg = - 1.125 kg	5.48 kg	-0.11 kg ^d -0.033 kg ^j -0.033 kg -0.099 kg = - 0.275 kg	5.21 kg	5.48 kg	4.80 kg
Total-P	1.13 kg ^e	No change	1.13 kg	No change	1.13 kg	1.13 kg	1.04 kg
Potassium (K)	2.85 kg ^f	No change	2.85 kg	No change	2.85 kg	2.85 kg	2.60 kg ^g

^a See table A.4^b N ex animal: 3.10 kg / 0.47 tonnes = 6.60 kg N per 1000 kg slurry (DJF, 2008a).^c The in-housing NH₃-emissions is 16% (pct. NH₃-N of total-N ex animal) (Poulsen et al., 2001) = 6.60 kg * 0.16 = 1.06 kg^d NH₃-emissions during storage is 2% (pct. NH₃-N of total-N ex housing) (Poulsen et al., 2001) = 5.54 * 0.02 = 0.11 kg^e P ex animal: 0.53 kg / 0.47 tonnes = 1.13 kg P per 1000 kg slurry (DJF, 2008a).^f K ex animal: 1.34 kg / 0.47 tonnes = 2.85 kg K per 1000 kg slurry (DJF, 2008a).^g The calculated potassium value (2.85 kg/1.086 = 2.62 kg) does not fit exactly to the DJF (2008a) "ex storage" value (2.60 kg). As the difference is less than 1%, the DJF (2008a) value is used.ⁱ In-house emissions, see table A.9. NH₃-N emissions: 1.06 kg. N₂O-N: 0.013 kg. NO-N: 0.013 kg. N₂-N: 0.039 kg. In total: -1.125 kg^j Storage emissions, see table A.11. NH₃-N emissions: 0.11 kg. N₂O-N: 0.033 kg. NO-N: 0.033 kg. N₂-N: 0.099 kg. In total: -0.275 kg

Table A.6.

Calculation of the "ex housing" characteristics of slurry from dairy cows (reference scenario)

	Ex animal	Mass balances and calculations				Ex housing	Ex storage
		In-housing change	Ex housing total (C) = (A)+(B)	Change during storage (D) (based on Poulsen et al., 2001)	Ex storage total (E) = (C)+(D)		
	(A) (based on DJF (2008a))	(B) (based on Poulsen et al., 2001)				(F) = (C) * 1000 kg/ 1000 kg ^a	(G) = (E) * 1000 kg/ 1044 kg ^a
Total mass	1000 kg Slurry ex animal	Not included ^a	1000 kg	+44 kg ^a	1044 kg	1000 kg Slurry ex housing	1000 kg Slurry ex storage
Total-N according to DJF, 2008a)	6.87 kg ^b	-0.55 kg ^c +0.09 kg ^d	6.41 kg	-0.13 kg ^e	6.28 kg	6.41 kg	6.02 kg
Used in this study: Total-N when including emissions of N ₂ O, NO and N ₂	6.87 kg ^b	-0.55 kg ^c +0.09 kg ^d -0.014 kg ^j -0.014 kg ^j -0.042 kg ^j = - 0.53 kg	6.34 kg	-0.13 kg ^e -0.034 kg ^k -0.034 kg ^k -0.10 kg ^k = - 0.3 kg	6.04 kg	6.34 kg	5.79 kg
Total-P	1.02 kg ^f	+0.012 kg ^h	1.03 kg	No change	1.03 kg	1.03 kg	0.98 kg
Potassium (K)	5.81 kg ^g	+0.09 kg ⁱ	5.90 kg	No change	5.90 kg	5.90 kg	5.65 kg

^a See table A.4^b N ex animal: 140.2 kg / 20.4 tonnes = 6.87 kg N per 1000 kg slurry (DJF, 2008a).^c The in-housing NH₃-emissions is 8% (pct. NH₃-N of total-N ex animal) (Poulsen et al., 2001) = 6.87 kg * 0.08 = 0.55 kg.^d According to Poulsen et al (2001), there is a consumption of 1.2 kg straw per cow per day for bedding. Straw contains 85% dry matter and 0.005 kg N per kg dry matter (Poulsen et al., (2001). Accordingly, the added amount of N during a year for a dairy cow is: 1.2 kg straw per animal * 365 days * 0.85 kg DM/kg straw * 0.005 kg N/kg DM = 1.8615 kg N. This amount corresponds to the total amount from a dairy cow during a year. As the dairy cow produces 20400 kg slurry (DJF (2008a)), the amount corresponds to 0.09 kg N per 1000 kg slurry. Note that according to DJF (2008b) 0.4 kg straw is added per day per animal, but it seems like DJF (2008a) has used the 1.2 kg straw per day from Poulsen et al. (2001).^e NH₃-emissions during storage is 2% (pct. NH₃-N of total-N ex housing) (Poulsen et al., 2001) = 6.41 * 0.02 = 0.13 kg^f P ex animal: 20.8 kg / 20.4 tonnes = 1.02 kg P per 1000 kg slurry (DJF, 2008a).^g K ex animal: 118.6 kg / 20.4 tonnes = 5.81 kg K per 1000 kg slurry (DJF, 2008a).^h The P content in straw is 0.00068 kg P per kg dry matter. The calculations are parallel to the calculations for N above: 1.2 kg straw per animal * 365 days * 0.85 kg DM/kg straw * 0.00068 kg P/kg DM / 20400 kg slurry = 0.012 kg P per 1000 kg slurry.ⁱ The K content in straw is 0.01475 kg K per kg dry matter. The calculations are parallel to the calculations for N above, however, it seems like that DJF (2008a) has used the amount of straw from DJF (2008b) i.e. 0.4 kg straw instead of the amount from Poulsen et al. (2001). 0.4 kg straw per animal * 365 days * 0.85 kg DM/kg straw * 0.01475 kg K per kg DM / 20400 kg slurry = 0.09 kg K per 1000 kg slurry.^j In-house emissions, see table A.9. NH₃-N emissions: 0.55 kg. N₂O-N: 0.014 kg. NO-N: 0.014 kg. N₂-N: 0.042 kg. In total: -0.53 kg^k In-house emissions, see table A.11. NH₃-N emissions: 0.13 kg. N₂O-N: 0.034 kg. NO-N: 0.034 kg. N₂-N: 0.10 kg. In total: -0.3 kg

A.1.4 Mass balances for Dry Matter, VS, Ash, Carbon, Cu and Zn

For dry matter, Poulsen et al. (2001) and DJF (2008a) only give data "ex storage". This also applies for all the data from other references, i.e. data are given "ex storage". Accordingly, the "ex housing" values and "ex animal" values have to be calculated "backwards":



The calculations for the rest of the parameters are shown in table A.7 (pigs) and A.8 (cows). The assumptions are described in the following text and the calculations are shown in the footnotes to the tables and to the text.

The dry matter (DM) content "ex storage" is based on the Danish Normative system for assessing manure composition (DJF, 2008a).

Dry matter "ex housing" and "ex animal" is calculated in accordance with the losses based on mass balances:



Table A.7.

Calculation of the "ex housing" and "ex animal" characteristics of slurry from fattening pigs for the reference scenario, for selected components other than N, P or K.

	Ex storage (A) (from references)	Mass balances and calculations		Ex housing (D) = (C) * 1086 kg/ 1000 kg ^a	Mass balances and calculations		Ex animal (G) = (F) * 1086 kg/ 1000 kg ^b
		Change during storage (B) (based on references)	Ex housing total (C) = (A)+(B)		In-housing change (E) (based on references)	Ex animal total (F) = (C)+(E)	
Total mass	1000 kg Slurry ex storage			1000 kg Slurry ex housing			1000 kg Slurry ex animal
Dry matter (DM)	61 kg	3.2 kg ^c	64.2 kg	69.7 kg	7.1 kg ^d	71.3 kg	77.4 kg
Ash content	12.2 kg (20% of DM ex storage)	No change	12.2 kg	13.2 kg	No change	12.2 kg	13.2 kg
Volatile solids (VS)	48.8 kg (80% of DM ex storage)	3.2 kg ^e	52 kg	56.5 kg	7.1 kg ^e	59.1 kg	64.2 kg
Of total VS:							
- easily degradable	28.1 kg	3.2 kg ^f	31.3 kg	34.0 kg	7.1 kg ^f	38.4 kg ^g	41.7 kg
- heavy degradable	20.7 kg	No change	20.7 kg	22.5 kg	No change	20.7 kg ^g	22.5 kg
Carbon (C)	29.2 kg ^h	1.5 kg ⁱ	30.7 kg	33.3 kg	3.4 kg ^j	34.1 kg	37.0 kg
Copper (Cu)	27.6 g ^k	No change	27.6 g	30.0 g	No change	27.6 g	30.0 kg
Zinc (Zn)	82.4 g ^k	No change	82.4 g	89.4 g	No change	82.4 g	89.4 kg
Density	1053 kg per m ³	No change		1053 kg per m ³	No change		1053 kg per m ³
pH	7.8	No change	7.8	7.8	No change	7.8	7.8

^a Adjusted by the relative amount of slurry: "amount of slurry ex storage"/"amount of slurry ex housing"

^b Adjusted by the relative amount of slurry: "amount of slurry ex storage"/"amount of slurry ex animal"

^c DM loss during storage corresponds to 5% of the "ex housing" value = 61 kg * 0.05/(1-0.05) = 3.2 kg

^d In-housing DM loss corresponds to 10% of the "ex animal" value = 64.2 kg * 0.10/(1-0.10) = 7.1 kg

^e It is assumed that the loss of volatile solids is identical to the loss of Dry Matter

^f It is assumed that all the volatile solids lost are easily degradable volatile solids

^g For pig slurry ex animal, 65% of the VS is easily degradable and 35% is heavily degradable, see text below.

^h Assumption for pig slurry: 47.9% of dry matter is C, see text below.

ⁱ Carbon loss during storage is assumed to be in the same order as the DM loss, i.e. 5% of the "ex housing" value.
C loss during storage = 29.2 kg * 0.05/(1-0.05) = 1.5 kg

^j The in-housing carbon loss is assumed to be in the same order as the DM loss, i.e. 10% of the "ex animal" value. C loss during storage = 30.7 kg * 0.10/(1-0.10) = 3.4 kg

^k For pig slurry 0.0453 % of the dry matter is copper and 0.135 % is zinc, see text below.

Table A.8.

Calculation of the "ex housing" and "ex animal" characteristics of slurry from dairy cows for the reference scenario, for selected components other than N, P or K.

	Ex storage	Mass balances and calculations		Ex housing	Mass balances and calculations		Ex animal
		Change during storage	Ex housing total		In-housing change	Ex animal total	
	(A) (from references)	(B) (based on references)	(C) = (A)+(B)	(D) = (C) * 1044 kg/ 1000 kg ^a	(E) (based on references)	(F) = (C)+(E)	(G) = (F) * 1044 kg/ 1000 kg ^b
Total mass	1000 kg Slurry ex storage			1000 kg Slurry ex housing			1000 kg Slurry ex animal
Dry matter (DM)	103 kg	5.4 kg ^c	108.4 kg	113.2 kg	12.0 kg ^d	120.4 kg	125.7 kg
Ash content	20.6 kg (20% of DM ex storage)	No change	20.6 kg	21.5 kg	No change	20.6 kg	21.5 kg
Volatile solids (VS)	82.4 kg (80% of DM ex storage)	5.4 kg ^e	87.8 kg	91.7 kg	12.0 kg ^e	99.8 kg	104.2 kg
Of total VS:							
- easily degradable	30.5 kg	5.4 kg ^f	35.9 kg	37.5 kg	12.0 kg ^f	47.9 kg ^g	50.0 kg
- heavy degradable	51.9 kg	No change	51.9 kg	54.2 kg	No change	51.9 kg	54.2 kg
Carbon (C)	45.2 kg ^h	2.4 kg ⁱ	47.6 kg	49.7 kg	5.3 kg ^j	52.9 kg	55.2 kg
Copper (Cu)	11.6 g ^k	No change	11.6 g	12.1 g	No change	11.6 g	12.1 kg
Zinc (Zn)	22.4 g ^k	No change	22.4 g	23.4 g	No change	22.4 g	23.4 kg
Density	1053 kg per m ³	No change		1053 kg per m ³	No change		1053 kg per m ³
pH	7.8	No change	7.8	7.8	No change	7.8	7.8

^a Adjusted by the relative amount of slurry: "amount of slurry ex storage"/"amount of slurry ex housing"

^b Adjusted by the relative amount of slurry: "amount of slurry ex storage"/"amount of slurry ex animal"

^c DM loss during storage corresponds to 5% of the "ex housing" value = 103 kg * 0.05/(1-0.05) = 5.4 kg

^d In-housing DM loss corresponds to 10% of the "ex animal" value = 108.4 kg * 0.10/(1-0.10) = 12.0 kg

^e It is assumed that the loss of volatile solids is identical to the loss of dry matter

^f It is assumed that all the loss of volatile solids is easily degradable volatile solids

^g For cattle slurry ex animal, 48% of the VS is easily degradable and 52% is heavily degradable, see text below.

^h Assumption for cattle slurry: 43.9% of dry matter is C, see text below.

ⁱ Carbon loss during storage is assumed to be in the same order as the DM loss, i.e. 5% of the "ex housing" value. C loss during storage = 45.2 kg * 0.05/(1-0.05) = 2.4 kg

^j The in-housing carbon loss is assumed to be in the same order as the DM loss, i.e. 10% of the "ex animal" value. C loss during storage = 47.6 kg * 0.10/(1-0.10) = 5.3 kg

^k For cattle slurry, 0.0113 % of the dry matter is copper and 0.0217 % is zinc.

During storage of slurry in-house and outdoor, there is a loss of dry matter due to microbial metabolisms and biochemical degradation. Poulsen et al. (2001) (page 130) and DJF (2008b) use an estimate for the in-housing loss of dry matter at 10% of the “ex animal” content of dry matter for slurry from pigs and cattle. The loss during storage is estimated to 5% of the “ex housing” content of dry matter for slurry (for pigs and cattle). The magnitudes of the losses depend to a great degree on the residence time for the slurry and the temperature. There are probably relatively high uncertainties related to this estimate, however, it has not been possible to identify better data for the loss of dry matter.

The ash is assumed to constitute 20% of the dry matter “ex storage” (estimate by Sommer et al. (2008)). It is assumed that there is no change in the ash amount from “ex animal” to “ex storage”.

The volatile solids (VS) are calculated as 80% of the dry matter “ex storage”. This is a rough estimate (Sommer et al., 2008) - but is nonetheless well in accordance with measurements made by S O Petersen (Personal communication with S O Petersen, December 2008).

The share of easily degradable VS and heavy degradable VS for pig slurry is based on Sommer et al. (2001, Appendix 5). Sommer et al. (2001) estimate that for pig slurry, 65% of the volatile solids are easily degradable and 35% are heavy degradable (“ex animal” values). For cattle slurry, 48% of the volatile solids are easily degradable and 52% are heavy degradable (“ex animal” values). Sommer et al. (2001) assume that all the loss of dry matter corresponds to loss of easily degradable VS.

Thus, the share of easily degradable VS and heavy degradable VS “ex housing” and “ex storage” can be calculated for fattening pigs and for dairy cows⁴.

⁴ The calculations for slurry from fattening pigs (fully slatted floors) is based on the following assumptions: DM “ex storage” is 61 kg (DJF, 2008a).
 The DM loss during storage is 5% of DM “ex housing” (DJF (2008b) and Poulsen et al. (2001), i.e. $DM(\text{storage loss}) = 61 \text{ kg} * 0.05 / (1 - 0.05) = 3.2 \text{ kg}$
 $DM \text{ “ex housing”} = DM \text{ “ex storage”} + DM(\text{storage loss}) = 61 \text{ kg} + 3.2 \text{ kg} = 64.2 \text{ kg}$
 The DM loss during housing: 10% of DM “ex housing” (DJF (2008b) and Poulsen et al. (2001), i.e. $DM(\text{housing loss}) = 64.2 \text{ kg} * 0.10 / (1 - 0.10) = 7.1 \text{ kg}$
 In Sommer et al. (2001) it is assumed that the loss of DM is identical to the loss of easily degradable VS. This is also identical to the loss of VS, as $VS = VS(\text{easily degradable}) + VS(\text{heavily degradable})$ and as the VS (heavily degradable) is not changed). I.e.:
 $VS \text{ “ex animal”} = VS \text{ “ex storage”} + DM(\text{storage loss}) + DM(\text{housing loss})$
 $VS \text{ “ex animal”} = 48.8 \text{ kg} + 3.2 \text{ kg} + 7.1 \text{ kg} = 59.1 \text{ kg}$
 Sommer et al. (2001) assume that 65% of the VS is easily degradable (“ex animal”) for pigs: $VS(\text{easily degradable, ex animal}) = 59.1 \text{ kg} * 0.65 = 38.4 \text{ kg}$
 As the loss of VS (easily degradable) is identical to the DM loss, the calculations are:
 $VS \text{ (easily degradable, ex housing)} = 38.4 \text{ kg} - 7.1 \text{ kg} = 31.3 \text{ kg}$
 $VS \text{ (easily degradable, ex storage)} = 31.3 \text{ kg} - 3.2 \text{ kg} = 28.1 \text{ kg}$
 Sommer et al. (2001) assumes that 35% of the VS is heavily degradable (“ex animal”) for pigs: $VS(\text{easily degradable, ex animal}) = 59.1 \text{ kg} * 0.35 = 20.7 \text{ kg}$.
 As it is assumed that the heavily degradable VS is unchanged in the housing units and during storage $VS \text{ (heavily degradable, ex housing)} = 20.7 \text{ kg}$ and $VS \text{ (heavily degradable, ex storage)} = 20.7 \text{ kg}$.
 The calculations for dairy cows follow the same assumptions as for pig slurry.

Data for carbon might be based directly on the measurements by Knudsen and Birkmose (2005): 28.1 kg C per 1000 kg cattle slurry and 18.2 kg C per 1000 kg pig slurry. However, the content of dry matter measured by Knudsen and Birkmose is significantly lower than the norm data by DJF (2007). Accordingly, it has been assumed that the ratio between carbon and dry matter from Knudsen and Birkmose (2005) can be used i.e. for pig slurry 47.9% of the dry matter is carbon and for cattle slurry, 43.9% of the dry matter is carbon⁵. It is assumed, that the loss of carbon is in the same proportion as the loss of dry matter, i.e. 5% during storage (DJF, 2008) and 10% in the housing units.

Data for copper and zinc are based on Knudsen and Birkmose (2005). The data from Knudsen and Birkmose (2005) are at the same level as Møller et al. (2007) (zinc in pig slurry is twice the amount in Knudsen and Birkmose (2005), which is still regarded as “at the same level” due to the high variations for the slurry). As argued above, the slurry defined by the Normative System (DJF, 2008a and Poulsen et al. 2000) is probably more concentrated than the measured data by Knudsen and Birkmose (2005) due to the fact that water in the housing units is not included in the Normative System. As for carbon, it is assumed that the ratio between copper and dry matter and the ratio between zinc and dry matter from Knudsen and Birkmose (2005) can be used, i.e.: for pig slurry 0.0453 % of the dry matter is copper and 0.135 % is zinc and for cattle slurry, 0.0113 % of the dry matter is copper and 0.0217 % is zinc. It is assumed that there is no gain or loss during storage.

The pH is set to 7.8 for the reference system for both pig slurry and cattle slurry, based on the measurements by Sommer and Husted (1995). Sommer and Husted (1995) found an average pH of 7.75 [7.2-8.3] for pig slurry and average pH of 7.84 [7.7-8.1] for cattle slurry. The raw pig slurry and cattle slurry was collected in the channels below the slatted floor of the animal housing.

The density of slurry has been set to 1053 kg per m³, based on the study by Sherlock et al. (2002). Lopez-Ridaura et al. (2008) use a density of 1034 kg per m³, which is not far from the value given by Sherlock et al. (2002). The density will most probably depend on a lot of factors (e.g. water, organic matter and salts in the slurry as well as it is affected by diets and management).

⁵ According to Knudsen and Birkmose (2005), pig slurry contains 38 kg dry matter and 18.2 kg C, i.e. 47.9% of the dry matter is carbon. Cattle slurry contains 64 kg dry matter per 1000 kg slurry and 28.1 kg C, i.e. 43.9% of the dry matter is carbon

A.2 In-house storage of slurry

A.2.1 System boundaries for the in-house storage of slurry

The life cycle inventory data for the slurry in the housing units includes the emissions from the slurry only (*not* including enteric fermentation) in accordance with the system boundaries described in chapter 2. The Life Cycle Inventory data for the in-house storage of slurry are shown in table A.9.

A.2.2 Emissions of CH₄ and CO₂

The CH₄ emissions from slurry in the housing units are based on the IPCC (2006) Tier 2 approach. According to this the CH₄ emissions are 3.29 kg CH₄ per 1000 kg pig slurry and 2.85 kg CH₄ per 1000 kg dairy cow slurry⁶

The uncertainty on the CH₄ emissions is high. The IPCC (2006) model use a very rough partitioning in “storage < 1 month” and “storage > 1 month”. The emission factors (in kg CH₄ per kg VS) is 5.67 times higher for “storage > 1 month” than for “storage < 1 month” which is an unrealistic jump. The emission of CH₄ should rather have been modelled as a function of time. In this study, the high emission factor from IPCC (2006) has been used as a conservative estimate. The CH₄ emissions depend on a range of factors, among these the CH₄ emissions to a great extent depend on the retention time in the housing units and on the biological activity. However, in the present study, the CH₄ emissions for the slurry management technologies are calculated relatively to the CH₄ emissions in the reference scenario, the significance of the uncertainty is therefore reduced slightly for the comparisons to the new technologies. Sensitivity analysis is carried out for the CH₄ emissions.

The emissions of CO₂ are based on a very rough estimate, as no data have been found. Sommer et al. (2008) state: ***“In most inventories or scenario calculations of carbon loss due to gaseous emissions are expressed as DM loss. The justification is partly that carbon is a major constituent of the organic matter in the***

⁶ According to IPCC (2006), the methane emission can be calculated as:

$$\text{CH}_4 [\text{kg}] = \text{VS} [\text{kg}] * B_0 * 0.67 [\text{kg CH}_4 \text{ per m}^3 \text{ CH}_4] * \text{MCF}$$

The VS amount is “ex animal”.

B₀ = 0.45 m³ CH₄ per kg VS for market swine (IPCC, 2006, Table 10A-7)

B₀ = 0.24 m³ CH₄ per kg VS for dairy cows (IPCC, 2006, Table 10A-4)

0.67 is the conversion factor from m³ CH₄ to kilograms CH₄

MCF = 17% for pit storage below animal confinements > 1 month (IPCC, 2006, Table 10-17)

MCF = 3% for pit storage below animal confinements < 1 month (IPCC, 2006, Table 10-17)

Calculation for fattening pig slurry, containing 64.2 kg VS per 1000 kg slurry (see table A.1 in this report), and assuming that the slurry is in the slurry pits > 1 month: CH₄ [kg] = 64.2 kg VS per 1000 kg slurry * 0.45 m³ CH₄ per kg VS * 0.67 [kg CH₄ per m³ CH₄] * 0.17 = 3.29 kg CH₄ per 1000 kg pig slurry “ex animal”.

Calculation for dairy cow slurry, containing 104.2 kg VS per 1000 kg slurry (see table A.2 in this report), and assuming that the slurry is in the slurry pits > 1 month: CH₄ [kg] = 104.2 kg VS per 1000 kg slurry * 0.24 m³ CH₄ per kg VS * 0.67 [kg CH₄ per m³ CH₄] * 0.17 = 2.85 kg CH₄ per 1000 kg dairy cow slurry “ex animal”.

DM fraction. Slurry is as mentioned an anaerobic matrix in which organic carbon transformation is relatively slow. The absence of oxygen is a precondition for the production of CO₂ and CH₄ via microbial metabolisms of organic material in livestock and livestock manure. During slurry storage inside the animal houses reduction in organic components will be affected by slurry removal frequency i.e. storage time and temperature. There are few studies of the reduction of DM under realistic conditions so in the Danish Normative system for assessing manure composition it has been decided that a rough estimate of DM loss from slurry stored in house is 10% (Poulsen et al. 2001)."

The CO₂ emissions are calculated as the total loss of carbon in the housing units minus the carbon lost as CH₄ emissions. The total carbon loss is calculated in table A.7 and A.8. The CO₂ emissions from the slurry in the slurry pits are estimated to 3.44 kg CO₂ for pig slurry⁷ and 11.6 kg CO₂ for dairy cow slurry⁸.

The uncertainty on the CO₂ emissions is very high, however, as methane has a much higher greenhouse gas potential (approximately 23 times as high as CO₂), the uncertainty on the CO₂ is not very important as the CH₄ emissions from the process is the main contributor to the global warming impact.

A.2.3 Emissions of NH₃, N₂O and other N compounds

The emissions of NH₃ are based on data from the Danish Normative system for assessing manure composition (Poulsen et al. (2007) and DJF (2007)). According to Poulsen et al. (2001), the emission factor for fattening pigs (fully slatted floor) is 16% NH₃-N of the total-N "ex animal". Thus, the emission of NH₃ from the slurry in the housing system is 1.06 kg NH₃-N per 1000 kg pig slurry "ex animal" (see calculations in table A.5). This value is at the same level as measured values by Kai et al. (2008) at 0.91 g NH₃-N per 1000 kg pig slurry "ex animal"⁹. It is, however, slightly lower than the emission coefficients suggested by Sommer et al. (2006), which corresponds to an emission of 1.3 NH₃-N per 1000 kg pig slurry "ex animal"¹⁰.

⁷ For fattening pigs: The carbon loss in the housing units is 3.4 kg (table A.7). The CH₄ emission is 3.29 kg (see table A.9), which corresponds to 3.29 kg * 12.011/(12.011 + 4*1.008) = 2.46 kg carbon. Carbon loss as CO₂-C = 3.4 kg - 2.46 kg = 0.94 kg CO₂-C. 0.94 kg CO₂-C which corresponds to 0.94 kg * (12.011 + 2 * 15.9994) / 12.011 = 3.44 kg CO₂.

⁸ For dairy cows: The carbon loss in the housing units is 5.3 kg (table A.8). The CH₄ emission is 2.85 kg (see table A.9), which corresponds to 2.85 kg * 12.011/(12.011 + 4*1.008) = 2.13 kg carbon. Carbon loss as CO₂-C = 5.3 kg - 2.13 kg = 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.

⁹ Kai et al. (2008) that found that an average NH₃-N emission from fattening pig housing units was 0.43 kg per pig produced (95% confidence interval 0.38–0.49 kg NH₃-N). As each pig produces 470 kg slurry the corresponding value is 0.91 g NH₃-N per 1000 kg pig slurry "ex animal".

¹⁰ Sommer et al. (2006) suggest an emission coefficient of 0.25 kg NH₃-N pr. kg TAN (NH₄⁺-N + NH₃-N) for fattening pigs in housing units with fully slatted floors. Assuming that pig slurry "ex animal" contains 79% NH₄⁺-N (Hansen et al., 2008),

The NH_3 emission factor for dairy cows (Cubicle housing system with slatted floor, 1.2 m channel) is 8% $\text{NH}_3\text{-N}$ of the total-N (excretion) (Poulsen et al., 2001). Thus the emission of NH_3 from the slurry in the housing system is 0.55 kg $\text{NH}_3\text{-N}$ per 1000 kg dairy cow slurry “ex animal” (see calculations in table A.6). Sommer et al. (2006) suggest an emission coefficient for cattle in cubicle housing units with slatted floors, corresponding to an emission of 0.68 $\text{NH}_3\text{-N}$ per 1000 kg dairy cow slurry “ex animal”¹¹, which is only 23% higher than the 0.55 kg $\text{NH}_3\text{-N}$ mentioned above.

The direct N_2O emissions in this study are based on IPCC (2006, table 10.21). IPCC (2006) estimates the N_2O emissions from pit storage below animal confinements to be 0.002 kg $\text{N}_2\text{O-N}$ per kg N “ex animal” (uncertainty: a factor 2), based on the judgement of an IPCC expert group combined with various studies.

The IPCC (2006) recommend including the indirect N_2O emissions, see description in IPCC (2006)¹². The indirect N_2O emission corresponds to 0.01 kg $\text{N}_2\text{O-N}$ per kg ($\text{NH}_3\text{-N} + \text{NO}_x\text{-N}$ volatilised) (IPCC, 2006, table 11.3).

Dämmgen and Hutchings (2008) developed a new approach for assessing emissions of gaseous nitrogen species from manure management. In their study, they assume that the emission of nitrogen monoxide (NO) is at the same level as the direct emissions of nitrous oxide (N_2O) (measured as NO-N and $\text{N}_2\text{O-N}$). Furthermore, they assume that emission of nitrogen (N_2) is three times as high as the direct emissions of nitrous oxide (N_2O) (measured as $\text{N}_2\text{-N}$ and $\text{N}_2\text{O-N}$). In the current study, it has not been possible to find data on NO_2 , however, due to the considerable uncertainty on the estimates on the NO emissions, it is assumed that the NO emissions represent the total NO_x emissions ($\text{NO}_x = \text{NO} + \text{NO}_2$).

and assuming that the pH is 7.8 which means that TAN are almost identical to the $\text{NH}_4^+\text{-N}$ amount, the NH_3 emission can be calculated as: 0.25 kg $\text{NH}_3\text{-N}$ pr. kg TAN * 6.60 kg N per 1000 kg pig slurry “ex animal” (see table A.1) * 0.79 = 1.3 kg NH_3 .

¹¹ Sommer et al. (2006) suggests an emission coefficient of 0.17 kg $\text{NH}_3\text{-N}$ pr. kg TAN ($\text{NH}_4^+\text{-N} + \text{NH}_3\text{-N}$) for cattle in cubicle housing units with slatted floors. Assuming that pig slurry “ex animal” contains 58% $\text{NH}_4^+\text{-N}$ (Hansen et al., 2008), and assuming that the pH is 7.8 which means that TAN are almost identical to the $\text{NH}_4^+\text{-N}$ amount, the NH_3 emission can be calculated as: 0.17 kg $\text{NH}_3\text{-N}$ pr. kg TAN * 6.87 kg N per 1000 kg pig slurry “ex animal” (see table A.2) * 0.58 = 0.68 kg NH_3 .

¹² From IPCC (2006, section 11.2.2): “In addition to the direct emissions of N_2O from managed soils that occur through a direct pathway (i.e., directly from the soils to which N is applied), emissions of N_2O also take place through two indirect pathways. The first of these pathways is the volatilisation of N as NH_3 and oxides of N (NO_x), and the deposition of these gases and their products NH_4^+ and NO_3^- - onto soils and the surface of lakes and other waters. “ and “The second pathway is the leaching and runoff from land of N from synthetic and organic fertiliser additions, crop residues, mineralisation of N associated with loss of soil C in mineral and drained/managed organic soils through land-use change or management practices, and urine and dung deposition from grazing animals. “ and “The nitrification and denitrification processes transform some of the NH_4^+ and NO_3^- - to N_2O .”

A.2.4 Discharges to water and soil

For both pig slurry and dairy cow slurry, it is assumed, that there are no emissions to water and soil from housing systems in the reference scenario, as leakages from housing systems are prohibited in Denmark (Poulsen et al. (2001), page 117).

A.2.5 Summary of the Life Cycle Inventory Data

The Life Cycle Inventory Data for storage of the slurry in the housing units are shown in table A.9. Feed for the animals, medicine, straw for bedding and water consumption are not included within the system boundary of the reference scenario.

Table A.9.

Life cycle Inventory data for storage of slurry in the housing units (reference scenario).
All data per 1000 kg of slurry "ex animal"

	Fattening pig slurry	Dairy cow slurry	Comments
Input			
Slurry "ex animal"	1000 kg	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	1000 kg	Please note that 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.
Energy consumption			
	Not included		The energy consumption for the housing units is not included within the system boundary of the reference scenario.
Emissions to air			
Carbon dioxide (CO ₂)	3.44 kg	11.6 kg	Estimate based on mass balances, see text.
Methane (CH ₄)	3.29 kg	2.85 kg	IPCC (2006) Tier 2 approach
Ammonia (NH ₃ -N)	1.06 kg	0.55 kg	Based on Poulsen et al. (2001) and DJF (2008). For fattening pig slurry (fully slatted floor): 16% NH ₃ -N of the total-N "ex animal". For dairy cows slurry (cubicle housing system with slatted floor): 8% NH ₃ -N of the total-N "ex animal". See table A.5 and A.6.
Direct emissions of Nitrous oxide (N ₂ O-N)	0.013 kg	0.014 kg	0.002 N ₂ O-N per kg N "ex animal" (IPCC, 2006). N "ex animal", see table A.1 and A.2.
Indirect emissions of Nitrous oxide (N ₂ O-N)	0.011 kg	0.006 kg	0.01 kg N ₂ O-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	0.014 kg	Estimates based on Dämmgen and Hutchings (2008), see text below.
Nitrogen dioxide (NO ₂ -N)	No data	No data	No data. Assumed to be represented by the NO emissions above.
Nitrogen (N ₂ -N)	0.039 kg	0.042 kg	Estimate based on Dämmgen and Hutchings (2008), see text below.
Discharges to water			
	None	None	Assumed to be zero, as leakages from housing systems are prohibited in Denmark.
Discharges to soil			
	None	None	Assumed to be zero, as leakages from housing systems are prohibited in Denmark.

A.3 Storage

A.3.1 System boundaries and description of the process “Storage”

The process called “Storage” includes emissions from:

- Storing slurry in the pre-tank (typically 2-6 weeks).
- Storing slurry in the outdoor storage for months before application to fields.

Furthermore, the energy consumption from pumping and stirring is included, i.e.:

- Flushing slurry from the slurry pits in the housing units to a pre-tank.
- Stirring slurry in the pre-tank before pumping to the outdoor storage.
- Pumping slurry from the pre-tank to the outdoor storage by a pump.
- Stirring slurry in the outdoor concrete tank when straw is added (pig slurry only)
- Stirring slurry before pumping from outdoor storage tank.
- Pumping slurry from the storage tank to the transport tank.

The emissions from these storage processes are treated together, as the available literature data for emissions are joined under “emissions during storage”. It would have been ideal to separate the pre-tank emissions from the outdoor storage emissions, but unfortunately, it has not been possible.

It is assumed that the emissions during this handling is negligible compared to the emissions from the outdoor storage.

The materials for the *pre-tank* (concrete etc.) are not included, as it is assumed to be more or less the same for in the reference scenario and for the alternative technologies. Preliminary calculations have shown that the construction of a concrete pre-tank (divided by the slurry amounts passing through the pre-tank during the life time of the pre-tank) is insignificant for the overall environmental impacts for slurry management.

In the reference scenarios, it is assumed that the slurry is stored in an outdoor concrete tank. LCA data for the concrete slurry storage tank is based on the Ecoinvent process: “Slurry store and processing, operation” (300 m³ concrete vessel, average life time 40 years). The process includes the production of a concrete vessel (divided by the amounts of slurry it contains during 40 years of use), production of a screw agitator and the electricity for stirring (the slurry is normally stirred before application to fields). The Ecoinvent data for the concrete store actually encompass a covered, under-floor slurry store, however, as preliminary calculations in SimaPro 7.1 has shown, that the slurry store is of minor significance for the overall results, it is acceptable.

As described in chapter 3, it is assumed that pig slurry is covered by cut straw. The amount corresponds to 2.5 kg per 1000 kg pig slurry (see section A.2). As straw is regarded as a waste product from grain production (rather than a co-product) the life cycle data of straw production is not included.

The energy consumption for cutting and adding straw has been left out as it is regarded as insignificant (there are only 2.5 kg straw per 1000 kg slurry i.e. less than 1% of the weight). As mentioned before, it is assumed that it is not

necessary to add cut straw to the cattle slurry (Rasmussen et al., 2001, page 31).

No additional chemicals or additives are added. During the storage, rain is adding water to the slurry. Accordingly, the total amount of slurry is slightly higher after storing, as described in the mass balances chapter 3. There are no wastes or by-products from the process.

A.3.2 Emissions of CH₄ and CO₂

The CH₄ emissions from outdoor storage of slurry are based on the IPCC (2006) Tier 2 approach. According to this the CH₄ emissions are 1.94 kg CH₄ per 1000 kg pig slurry and 1.68 kg CH₄ per 1000 kg dairy cow slurry¹³. The CH₄ emissions based on IPCC (2006) are at the same level as modelled by Sommer et al. (2001). For the outdoor storage of slurry, Sommer et al. (2001) modelled the CH₄ emissions to 2.07 kg CH₄ per 1000 kg pig slurry¹⁴ and 1.61 kg CH₄ per 1000 kg cattle slurry¹⁵. There is significant uncertainty related to the magnitude of the CH₄ emissions as discussed in Olesen et al. (2004, Annex B). A scientific discussion regarding various estimates and investigations is beyond the scope of this study.

The liquid slurry is usually homogenized (stirred) in the tank prior to application. Mixing may release H₂S and CH₄. It is assumed that the amount of CH₄ emissions during stirring are minor compared to the loss during storage, hence, only emissions during storage and application is included in this study.

The CO₂ emissions for the outdoor storage are calculated as the in-housing CO₂ emissions in section A.2, i.e. the total loss of carbon in the housing units

¹³ According to IPCC (2006), the methane emission can be calculated as:

$$\text{CH}_4 [\text{kg}] = \text{VS} [\text{kg}] * B_0 * 0.67 [\text{kg CH}_4 \text{ per m}^3 \text{ CH}_4] * \text{MCF}$$

The VS amount is “ex animal”.

$B_0 = 0.45 \text{ m}^3 \text{ CH}_4 \text{ per kg VS}$ for market swine (IPCC, 2006, Table 10A-7)

$B_0 = 0.24 \text{ m}^3 \text{ CH}_4 \text{ per kg VS}$ for dairy cows (IPCC, 2006, Table 10A-4)

0.67 is the conversion factor of m³ CH₄ to kilograms CH₄

MCF = 10% for liquid slurry with natural crust cover, cool climate (IPCC, 2006, Table 10-17)

Calculation for fattening pig slurry, containing 64.2 kg VS per 1000 kg slurry (see table A.1 in this report), and assuming that the slurry is in the slurry pits > 1 month:
 $\text{CH}_4 [\text{kg}] = 64.2 \text{ kg VS per 1000 kg slurry “ex animal”} * 0.45 \text{ m}^3 \text{ CH}_4 \text{ per kg VS} * 0.67 [\text{kg CH}_4 \text{ per m}^3 \text{ CH}_4] * 0.10 = 1.94 \text{ kg CH}_4 \text{ per 1000 kg pig slurry “ex animal”}$
(which is identical to 1.94 kg CH₄ per 1000 kg pig slurry “ex housing”).

Calculation for dairy cow slurry, containing 104.2 kg VS per 1000 kg slurry (see table A.2 in this report), and assuming that the slurry is in the slurry pits > 1 month:
 $\text{CH}_4 [\text{kg}] = 104.2 \text{ kg VS per 1000 kg slurry “ex animal”} * 0.24 \text{ m}^3 \text{ CH}_4 \text{ per kg VS} * 0.67 [\text{kg CH}_4 \text{ per m}^3 \text{ CH}_4] * 0.10 = 1.68 \text{ kg CH}_4 \text{ per 1000 kg dairy cow slurry “ex animal”}$
(which is identical to 1.68 kg CH₄ per 1000 kg pig slurry “ex housing”).

¹⁴ Sommer et al. (2001), Appendix 3: 0.7744 kg CO₂-eqv per kg VS excreted / 21 CO₂-eqv per kg CH₄ * 56 kg VS per 1000 kg pig slurry (Sommer et al. (2001, page 44) = 2.07 kg CH₄ per 1000 kg pig slurry.

¹⁵ Sommer et al. (2001), Appendix 3: 0.4222 kg CO₂-eqv per kg VS excreted / 21 CO₂-eqv per kg CH₄ * 80 kg VS per 1000 kg cattle slurry (Sommer et al. (2001, page 44) = 1.61 kg CH₄ per 1000 kg cattle slurry.

minus the carbon lost as CH₄ emissions. The total carbon loss is calculated in table A.7 and A.8. The CO₂ emissions from the slurry in the slurry pits are estimated to 0.18 kg CO₂ for pig slurry¹⁶ and 4.21 kg CO₂ for dairy cow slurry¹⁷.

Loyon et al. (2007) measured gaseous emissions from aerobic treatment of pig slurry and compared this to the emissions from a conventional storage system. Calculations on their results from the “conventional storage system” show that the CO₂-C emissions corresponds to 78% of the CH₄-C emissions (i.e. when there are 100 grams of CH₄-C emissions there will be 78 grams of CO₂-C). Sneath et al. (2006) monitored green house gas emissions from covered manure stores on dairy farms. When comparing the CO₂ and CH₄ emissions from Sneath et al. (2006) it can be seen that for each time, 100 grams of CH₄-C is emitted, approximately 120 grams of CO₂-C is emitted. The ratio of CH₄ and CO₂ depends on the proportion of the biological processes. Møller et al. (2004) found a high biological degradation in the aerobic surface layers of the stored manure at 15°C leading to CO₂ emissions. As mentioned in section A.3, the uncertainty on the CO₂ emissions is very high however, as methane is a greenhouse gas, with a much higher global warming potential as compared with CO₂, the uncertainty on the CO₂ is not very important, since the CH₄ emissions from the process are in the main contributor to the global warming.

A.3.3 Emissions of NH₃, N₂O and other N compounds

The NH₃ emissions are based on Poulsen et al. (2001, page 119). Poulsen et al. (2001) presume that the slurry tank is 4 meter deep and that the storage time is 12 months (page 128 in Poulsen et al, 2001). A storage time of 12 months might be “in the high end”. According to Poulsen et al. (2001), the emission of NH₃-N is 2% of the total-N in the slurry “ex housing” for both pigs and cattle (see the calculations in table A.5 and A.6).

The direct N₂O, emissions are based on IPCC (2006). IPCC (2006) recommend an emission factor of 0.005 kg N₂O-N per kg N “ex animal” for slurry stored with natural crust cover. IPCC (2006) estimate the uncertainty to be a factor 2. As the IPCC factor is “ex animal”, it means that difference in the various housing units and the biological degradation in the housing units (which might change the total content of N in the slurry) is not taken into consideration. However, it has not been possible to make a better approximation within the framework of this study.

¹⁶ For fattening pigs: The carbon loss during storage 1.5 kg (table A.7).
 The CH₄ emission is 1.94 kg (see table A.9), which corresponds to 1.94 kg *
 $12.011 / (12.011 + 4 * 1.008) = 1.45$ kg carbon.
 Carbon loss as CO₂ = 1.5 kg – 1.45 kg = 0.05 kg C, which corresponds to 0.05 kg *
 $(12.011 + 2 * 15.9994) / 12.011 = 0.18$ kg CO₂

¹⁷ For dairy cows: The carbon loss in the housing units is 2.4 kg (table A.8).
 The CH₄ emission is 1.68 kg (see table A.9), which corresponds to 1.68 kg *
 $12.011 / (12.011 + 4 * 1.008) = 1.25$ kg carbon.
 Carbon loss as CO₂ = 2.4 kg – 1.25 kg = 1.15 kg C, which corresponds to 1.15 kg *
 $(12.011 + 2 * 15.9994) / 12.011 = 4.21$ kg CO₂

In addition, the indirect N₂O emission has been included in accordance with the IPCC (2006) guidelines, as described in section A.2, i.e. 0.01 kg N₂O-N per kg (NH₃-N + NO_x-N volatilised) (IPCC, 2006, table 11.3).

The NO and N₂ emissions are based on the rough estimate by Dämmgen and Hutchings (2008), as for the NO and N₂ emissions in the housing units, see section A.3.

A.3.4 Discharges to water and soil

It is assumed, that there are no emissions to water and soil from slurry storage in the reference scenario, as leakages from slurry tanks are prohibited in Denmark (Poulsen et al. (2001), page 117).

A.3.5 Energy consumption for pumping and stirring

The energy consumption for pumping and stirring in the reference scenario is shown in table A.10.

The energy and water for *flushing* the slurry from the slurry pits in housing units to the pre-tank is not included. It is assumed that it is more or less identical in the reference scenario and in the scenarios for the alternative technologies and that a potential difference in how this is done is insignificant for the overall environmental impacts for slurry management.

It is assumed that the energy consumption for the *stirring* is 1.22 kWh [0.71-2.41] per 1000 kg slurry (Personal communication with J Mertz (2008) based on communication with farmer). The Ecoinvent database contains the process “Slurry store and processing”, which contains data for a covered, under-floor slurry store including a 6 kW marine screw agitator. According to the Ecoinvent data, the energy consumption used by the agitator is approximately 0.4 kWh per 1000 kg slurry. In this study, the energy consumption for stirring is assumed to be 1.2 kWh per 1000 kg slurry.

According to Sandars et al. (2003), the energy consumption for *pumping* slurry in a pipeline from housing to storage is in the range of 0.2-0.5 kWh per 1000 kg slurry. They base their data on various pump manufacturers. Obviously, the energy required depends on factors like slurry density, distance travelled, flow rate, velocity etc. The transport from the slurry tank to the slurry transport tanker can alternatively be carried out by the use of a tractor with a diesel engine corresponding to a consumption of 60-70 litres for 1000 m³ slurry (which corresponds to approximately 0.5 kWh per 1000 kg slurry)¹⁸. In this study, the energy consumption for pumping is presumed to be 0.5 kWh electricity per 1000 kg slurry.

Data for producing the pump has not been included. Preliminary calculations in SimaPro 7.1 by the use of the Ecoinvent data mentioned above (for the process “Slurry store and processing”) showed that the production of the pump was insignificant compared to the energy consumption during use of the pump.

¹⁸ 0.06-0.07 litres diesel per 1 m³ slurry * 42.7 MJ/kg * 0.82 kg/litre / 3.6 MJ/kWh / 1.053 kg slurry per m³ = 0.55-0.65 kWh per 1000 kg slurry.

When adding straw to pig slurry for floating layer, stirring is required (by law) and accordingly, stirring is included twice for pig slurry in the storage tank (i.e. when adding straw and before pumping the slurry to the transport container). The total energy consumption for stirring and pumping is shown in table A.10.

Table A.10
Energy consumption for stirring and pumping slurry during storage. All data are expressed per 1000 kg of slurry “ex housing”.

	Fattening pig slurry	Dairy cow slurry
Electricity for stirring in the pre-tank before pumping.	1.2 kWh	1.2 kWh
Electricity for pumping from the pre-tank to the outdoor storage.	0.5 kWh	0.5 kWh
Electricity for stirring in the outdoor concrete tank when straw is added (pig slurry only)	1.2 kWh	-
Electricity for stirring in the outdoor concrete tank before pumping to transport container.	1.2 kWh	1.2 kWh
Electricity for pumping from the storage tank to the transport container.	0.5 kWh	0.5 kWh
Total	4.6 kWh	3.4 kWh

A.3.6 Electricity production

The modelling of marginal electricity in Denmark is based on Lund et al. (2009). According to this, the marginal electricity shall be modelled as be modelled as “Business as Usual + Power Plant Natural gas” (table 3 in Lund et al. ,2009), i.e. 1% wind, 49% Power Plant (coal), 18% Power Plant (natural gas), 9% large Combined Heat and Power plant (natural gas), 2% large Combined Heat and Power plant (coal), 16% small Combined Heat and Power plant (natural gas) and 5% electric boiler.

The marginal electricity production in Life Cycle Assessments is normally either coal or natural gas (Lund et al., 2009), accordingly these have been used for the sensitivity analysis.

A.3.7 Summary of the Life Cycle Inventory Data

Table A.11 presents an overview of the life cycle inventory data used in this project as regarding the storage of slurry, for both pigs and cows’ slurry. The inputs to the processes are 1000 kg of slurry “ex housing”. All emissions and consumptions are calculated relative to this 1000 kg of slurry going into the process.

Table A.11

Life cycle data for storage of slurry (reference scenario). All data per 1000 kg of slurry "ex housing".

	Fattening pig slurry	Dairy cow slurry	Comments
Input			
Slurry "ex housing"	1000 kg	1000 kg	The reference slurry for the process "Storage" is slurry "ex housing" i.e. the emissions are calculated relative to this.
Cut straw	2.5 kg	None	Cut straw is added for floating layer during storage for pig slurry. It is assumed that it is not necessary to add cut straw to the cattle slurry (Rasmussen et al., 2001, page 31).
Concrete slurry store	Included	Included	Estimates based on data from the Ecoinvent process: "Slurry store and processing, operation", see text above.
Output			
Slurry "ex storage"	1086 kg	1044 kg	See mass balance in table A.4.
Energy consumption			
	4.6 kWh	3.4 kWh	Energy consumption for pumping and stirring.
Emissions to air			
Carbon dioxide (CO ₂)	0.18 kg	4.21 kg	Rough estimate based on mass balance, see text.
Methane (CH ₄)	1.94 kg	1.68 kg	IPCC (2006), Tier 2 approach
Ammonia (NH ₃ -N)	0.11 kg	0.13 kg	Emission of NH ₃ -N is 2% of the total-N in the slurry "ex housing" based on Poulsen et al. (2001). See table A.5 and A.6.
Direct emissions of Nitrous oxide (N ₂ O-N)	0.033 kg	0.034 kg	0.005 kg N ₂ O-N per kg N "ex animal". Ref: IPCC (2006). N "ex animal" is based on DJF (2008a), see table A.5 and A.6.
Indirect emissions of Nitrous oxide (N ₂ O-N)	0.0014 kg	0.0016 kg	0.01 kg N ₂ O-N per kg (NH ₃ -N + NO _x -N) volatilised (IPCC, 2006, table 11.3). Ammonia emissions given in this table.
Nitrogen monoxide (NO-N) (representing total NO _x)	0.033 kg	0.034 kg	Estimate based on Dämmgen and Hutchings (2008), see text.
Nitrogen dioxide (NO ₂ -N)	No data	Not data	No data. Assumed to be represented by the NO emissions.
Nitrogen (N ₂ -N)	0.099 kg	0.10 kg	Estimate based on Dämmgen and Hutchings (2008), see text.
Discharges to water			
	None	None	Assumed to be zero, as leakages from slurry tanks are prohibited in Denmark
Discharges to soil			
	None	None	Assumed to be zero, as leakages from slurry tanks are prohibited in Denmark

A.4 Transport to field

A.4.1 System boundaries and description of the process “Transport to field”

The transport of slurry to the fields can be carried out by a tractor with trailer or by truck. For small distances, it is common to use a tractor with trailer and for long distances, a truck is used. According to Pedersen et al. (2007), the trucks transport capacity is up to 35 m³ per trip.

Transport of the slurry from the slurry tank to the fields is estimated to 10 km, as described in section 3.2. Sensitivity analysis has been made for this assumption with 2 km and 32 km. Data for the transport is based on a mix of data from the Ecoinvent process “Transport, tractor and trailer” (10 km). For the longer distances in the sensitivity analysis, the transport above 10 km is modelled by the Ecoinvent process “Transport, lorry >32t, EURO3”. The Ecoinvent data includes the production of the tractor, trailer and truck (which is a relatively small amount, as it is divided in proportion to all the transport in the entire lifetime of the vehicles).

Emissions from the slurry to air during transport are assumed to be negligible compared to the emissions in the housing units, during storage and during application of slurry, as these emissions are not included in Poulsen et al. (2001), Nielsen et al. (2008a) or Nielsen et al. (2008b).

A.4.2 Summary of the Life Cycle Inventory Data

Table A.12.
Life cycle data for transport to field (reference scenario). All data per 1000 kg of slurry “ex storage”.

	Fattening pig slurry	Dairy cow slurry	Comments
Input			
Slurry “ex storage”	1000 kg	1000 kg	This is the reference amount of slurry. The emissions are calculated relative to this.
Output			
Slurry “ex storage”	1000 kg	1000 kg	
Energy consumption			
Transport	10 km	10 km	Transport data from the Ecoinvent database. 10 km “Transport, tractor and trailer” Sensitivity analysis performed for 2-32 km by adding 22 km by “Transport, lorry >32t, EURO3” The Ecoinvent process includes the construction of the tractor, trailer and truck.
Discharges to air			
	Included	Included	The emissions from transport are included in the Ecoinvent process.

A.5 Field processes

A.5.1 System boundaries and description of the process “Field Processes”

The process called “Field processes” includes:

- Application of slurry by trail hose application tanker (including diesel for the tractor and production of tractor).
- Emissions to air during application
- Emissions to air during the following period.
- Emissions to water (leaching of N and P)
- Uptake of N. The slurry content of N is assumed to replace mineral N fertiliser (the degree depends on the type of slurry).
- Uptake of phosphorus. It is assumed that the slurry content of P replaces mineral P fertiliser 1:1.
- Uptake of potassium. It is assumed that the slurry content of K replaces mineral K fertiliser 1:1.
- Storage of carbon in the soil. The C-TOOL model complex will be used for estimating C storage in the soil, using the methods described in Gyldenkerne et al. (2007).

The crops on the fields are not included within the system boundaries, as mentioned in chapter 2 under system boundaries.

The life cycle inventory data for application of slurry is shown in table A.17.

The Ecoinvent database contains no data for spreading slurry by trail hose application tanker. As a proxy, data from the Ecoinvent process “Slurry spreading, by vacuum tanker” has been used. The process includes the diesel for slurry application, construction of the tractor, the slurry tanker and a shed, all divided by their estimated life time and slurry amount in this period. The emissions from the combustion of the diesel in the tractor motor are included. The Ecoinvent process includes a diesel consumption corresponding to 0.25 litre diesel per 1000 kg slurry. The diesel consumption in Ecoinvent is at the same level as the 0.3 litre diesel per 1000 kg slurry estimated for slurry spreading by Dalgaard et al. (2002). Adamsen (2004, table 8) estimates a diesel consumption of 0.67 litres of diesel per 1000 kg of slurry for application of 30 tons of slurry per ha. M Kjelddal (2009) estimates that application of slurry by trail hoses consumes approximately 0.4 litres of diesel per 1000 kg of slurry. The calculations are based on the estimate by M Kjelddal (2009), modelled by adjusting the Ecoinvent data to 0.4 litres of diesel per 1000 kg of slurry.

A.5.2 Emissions of CH₄ and CO₂

The CH₄ emission on the field is assumed to be negligible, as the formation of CH₄ requires an anaerobic environment, which is under normal conditions not the case in the topsoil.

CO₂ emissions are modeled by the dynamic soil organic matter model C-TOOL (Petersen et al., 2002; Gyldenkerne et al., 2008). The development in organic soil N is modeled by assuming a 10:1 ratio in the C to N development.

A.5.3 Emissions of NH₃, N₂O and other N compounds

Significant amounts of NH₃ are lost in the period after application. The NH₃ emissions occurring after application are based on Hansen et al. (2008) (as recommended by T Birkemose, personal communication January 2009). According to Hansen et al. (2008, page 23), the emissions of NH₃ during the very application corresponds to 0.5% of the TAN for trail hose application. In this context, it is assumed that the amount of TAN (NH₃+ NH₄⁺) is the same as the amount of NH₄⁺ ex storage, which is a reasonable approximation at pH 7.8. NH₄⁺-N “ex storage” is calculated as 79% of the total N for fattening pigs and as 58% of the total N for dairy cows (Hansen et al., 2008). Poulsen et al. (2001, page 130) and DJF (2008b) give an estimate of 75% for pig slurry and 60% for cattle slurry, however, this is not used in their calculations (personal communication, H Damgaard Poulsen, January 2008). As the proportions in Hansen et al. (2008) are based on measurements of more than 500 slurry samples, and as the calculation of the ammonia emissions occurring during application based on data from Hansen et al. (2008), the 79% for pig slurry and 58% for cattle slurry from Hansen et al. (2008) is used in this study for the calculation of NH₃ emissions occurring after application..

It should however be emphasized that there is a huge uncertainty connected to the amount of NH₃ emitted after application. In fact, the NH₃-emissions depend on a variety of factors, e.g. application method, soil type, weather (sun/ overcast sky), temperature, wind speed and height of the crop. Accordingly, it is not possible to identify the “true” emission. The values in Hansen et al. (2008) are based on model calculations verified by measurements. The emission factors for trail hose application for the most typical application times from Hansen et al. (2008, page 33) is shown in table A.13. When there is application to a soil without crop, it is assumed that the slurry is ploughed down after a maximum of 6 hours, as this is required by law in Denmark (Hansen et al., 2008).

Table A.13.

NH₃ emissions after application, based on Hansen et al. (2008). Emissions are expressed in NH₃-N loss in percent of NH₄⁺-N content in the slurry at the time of application.

Season	Crop	Technology	Pig slurry NH ₃ -N loss in percent of NH ₄ ⁺ -N content in the slurry ^a	Cattle slurry
Spring	No crop	Trail hose application, after maximum 6 hours the slurry is ploughed down	5.0	9.4
	Cereal/grain	Trail hose application	14.8	28.1
	Grass	Trail hose application	17.1	32.6
Summer	No crop	Trail hose application, after maximum 6 hours the slurry is ploughed down	6.5	12.4
	Grass	Trail hose application	22.3	42.5
Autumn	Grass	Trail hose application	21.8	41.6

^a Hansen et al. (2008) use a relation between NH₄⁺-N and total-N in slurry of 79% for pig slurry and 58% for cattle slurry.

It is assumed that the slurry is partitioned in the crop rotation as specified in section 3.1. Taking pig slurry application to winter wheat as an example of the calculation, 133.5 (see section 3.1) kg N ha⁻¹ in slurry is assumed applied in April. According to Hansen et al. (2008) the loss is 14.8 % of TAN.

Assuming a TAN content of 58% of the total N content, the loss from soil and leaves becomes $133.5 \text{ kg N ha}^{-1} * 0.58 * 0.148 = 11.46 \text{ kg N ha}^{-1}$, in addition to the spreading loss itself of 0.5% of TAN, which is $133.5 \text{ kg N ha}^{-1} * 0.05 = 0.67 \text{ kg N ha}^{-1}$, totalling $12.13 \text{ kg N ha}^{-1}$.

When performing an area and slurry-N weighed average of all the losses in the crop rotation, a loss of $0.138 \text{ g NH}_3\text{-N per g TAN}$ in the pig slurry is obtained. For cattle slurry, the equivalent emission coefficient becomes $0.217 \text{ g NH}_3\text{-N per g TAN}$ in the slurry. The two latter coefficients includes the spreading loss of 0.5%.

The NH_3 emissions for pig slurry thus become $0.50 \text{ kg NH}_3\text{-N per 1000 kg pig slurry}$ ¹⁹ and $0.75 \text{ kg NH}_3\text{-N per 1000 kg cattle slurry}$ ²⁰

It should be emphasized that there are significant uncertainties related to the NH_3 emissions. Nielsen et al. (2008b) use an emission factor of 5% of N “ex storage” as basis for the Annual Danish Emission Inventory Report to UNECE. In Sommer and Hansen (2004) it is shown that for cattle slurry the NH_3 emission can vary from 4- 26% of the $\text{NH}_4^+\text{-N}$ “ex storage” (trail hose application tanker on winter wheat). For pig slurry the NH_3 emissions was in the range of 3-18% $\text{NH}_4^+\text{-N}$ “ex storage” (trail hose application tanker on winter wheat). There were huge variations due to season, temperature and height of the crop. Kai et al. (2008) found a significantly higher emission factor: The NH_3 emission corresponded to almost 50% of the applied $\text{NH}_4^+\text{-N}$ “ex storage” during a 7 days period (pig slurry applied by trail hose application tanker on sandy loam soil with 5% clay).

A.5.4 Emissions of N_2O and NO_x

The direct N_2O emissions are $0.01 \text{ kg N}_2\text{O-N per kg N}$ “ex storage” for application of animal wastes to soil, based on IPCC (2006, table 11.1). The uncertainty range is $0.003 - 0.03 \text{ kg N}_2\text{O-N per kg N}$ “ex storage”.

In addition, the indirect N_2O emissions have been included in accordance with the IPCC (2006) guidelines, as described in section A.2, i.e. $0.01 \text{ kg N}_2\text{O-N per kg (NH}_3\text{-N + NO}_x\text{-N volatilised)}$ (IPCC, 2006, table 11.3).

Nitrate leaching also lead to indirect N_2O emission, corresponding to $0.0075 \text{ kg N}_2\text{O-N per kg N leaching/runoff}$ (IPCC, 2006, table 11.3).

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: $\text{NO}_x = 0.21 * \text{N}_2\text{O}$. When taking the molar weights into consideration (assuming $\text{NO}_x = \text{NO}_2$) this corresponds to $\text{NO}_x\text{-N} = 0.1 * \text{N}_2\text{O-N}$. It is considered that it is a “rough expert estimate”, however, as the relative contribution has minor significance for the overall results, it is considered to be adequate.

The N_2 emissions are based on the estimates from SimDen (Vinther, 2004).

¹⁹ For pig slurry: $0.138 \text{ g NH}_3\text{-N per g NH}_4^+\text{-N in the slurry}$ “ex storage” * $0.75 \text{ kg NH}_4^+\text{-N per kg N}$ * $4.80 \text{ kg N} = 0.50 \text{ kg}$

²⁰ For cattle slurry: $0.217 \text{ g NH}_3\text{-N per g NH}_4^+\text{-N in the slurry}$ “ex storage” * $0.60 \text{ kg NH}_4^+\text{-N per kg N}$ * $5.79 \text{ kg N} = 0.75 \text{ kg}$

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.

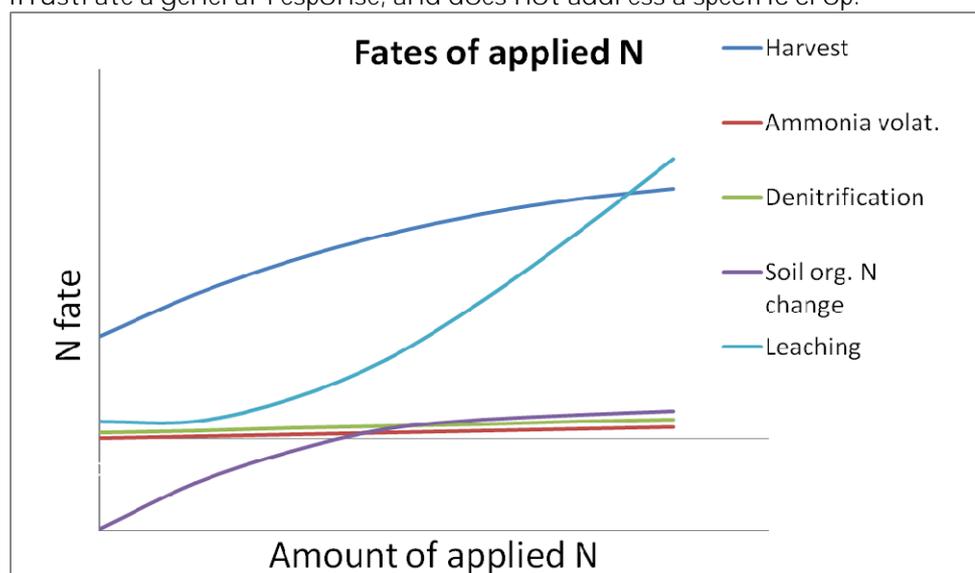
A.5.5 Nitrogen leaching

Once applied to the field, the N from both mineral and animal fertiliser is assumed to have a limited number of fates: ammonia volatilization, emission from nitrous gasses, removal by harvest, incorporation in the pool of soil organic matter and finally nitrogen leaching. Nitrogen leaching is predominantly in the form of nitrate-N, but may also occur in the form of ammonia and organic N. In a Danish context, erosion losses of N can largely be ignored. The crop net ammonia exchange is very small and uncertain. Utilizing consequential LCA, the focus is on marginal changes, which in the case of the soil-crop system with focus on slurry means changes in the amount of applied mineral N and slurry composition changes.

To illustrate this, Figure A.2 shows the postulated response of a grain crop to available mineral N.

Figure A.2.

N flows at different levels of mineral N fertilisation. This figure is meant to illustrate a general response, and does not address a specific crop.



The responses are non-linear, and it falls out of the scope of this project to estimate all the relevant response curves. But for this purpose, many of the responses may be treated as linear, because they have rather small amplitudes. Take the harvested N in figure A.2 as an example. The value of this will only change slightly due to the different slurry treatments. So what need to be determined here are mainly linear slopes within small intervals.

Looking again at figure A.2, it is apparent that the leaching loss curve to a large extent is the inverse of the N harvested curve, and under predominate Danish conditions these are the two major fates of field N input. So an essential precondition for good N leaching response estimates is good estimates for N uptake responses in the harvested part of the crop. Unfortunately, the two dynamic models developed for Danish conditions (Daisy, Hansen et al., 1991 and FASSET, Berntsen et al., 2003) are not at

present refined to a point where they give very accurate responses of N yield to applied N. One of the problems related to this, is that the N yield at no N application for both models is significantly lower than typical measured values, which crudely put “twists” the entire N response curve for both models. For a more comprehensive discussion on the use of dynamic models, see Petersen et al. (2007).

The FarmN model, derived on the basis of the recommendations in (Petersen et al., 2007) is developed with the aim of giving robust N emission estimates at average yield levels, but does not have an explicit N yield curve, and therefore is not suited for this specific purpose either, because of the pivotal importance of the marginal N responses of the fates of figure A.2. For the present purpose, we therefore take basis in measured N yield responses, where Landscentret has performed a very large number of field trials throughout Denmark, with different levels of added mineral N. Pedersen (2008) provides an overview of the national field trials for the later years. This study draws on data from the period 19988 – 2008, with data kindly provided by Leif Knudsen, Landscentret. We utilize information on winter wheat and spring barley, as these are the most common grain crops. At the level of norm fertilisation, the grain yield N recovers approx 36.6 % of the added N on JB3 and 39.9 % on JB6. At lower N levels, the recovery is up to approx. 40% and 50 %, respectively, supporting the non-linear response outlined in figure A.2. For spring barley, the corresponding recoveries are approx. 23.8 % (JB3) and 27.5 % (JB6), with recoveries up to respectively 43 % and 36 %, respectively, at lower N levels. These values are calculated by taking the grain N yield response (3rd order polynomium approximation, corrected for N carry-over effect of the previous crop) at the norm N fertilisation level.

For simplicity, it is assumed that 50% of the available straw is bailed, and 50% left on the field. This may differ a lot from region to region and farm type to farm type, though. At dairy farms a lot of straw would typically be bailed for own use, while at pig farms the straw would typically either be left on the field or sold. According to Danmarks Statistik (2008), 43 % of the straw in Denmark is left on the field. For both crops, the available straw constitutes 23 % of the dry matter in grain, after Gyldenkærne et al. (2007, Table A1).

According to Landbrugets Rådgivningscenter (2005) the protein concentration in wheat straw is approx. 29% of the concentration in grain. By harvesting the above amount of straw, the marginal harvested N rises to 39.1 % (JB3) and 42.6 % (JB6). The protein concentration in barley straw is approx. 37 % of the grain concentration, whereby the marginal N harvest rises to 25.8 % (JB3) and 29.9 % (JB6). For grain-rich crop rotations, we use the average values of winter wheat and spring barley, giving recoveries of 32.5 % (JB3) and 36.2 % (JB6). Bearing in mind that the responses are obtained from 1-year trials, a significant part of the N in plant residues, and to some extent possible mineral N remainders in the soil after harvest will be available for the following crops. It is crudely assumed that 50 % of the surplus N is lost by leaching after harvest, both caused by mineral N remainders and rapid initial N mineralization in autumn.

The majority of the remaining 50 % is assumed to become available by mineralisation of organic bound N. Therefore the plant uptake “value” of mineralized N versus N from mineral N in fertilizer must be determined. In

Petersen et al. (2006, Appendix H), the plant uptake value of mineralized N relative to mineral fertilizer is an average of 65.3 % on JB3 and 73.0 % on JB6. So a significant proportion of the mineralized N is re-utilised by the subsequent crops. Correcting the above marginal harvest N estimates for this effect we obtain $32.5 + 32.5 * 65.3/100 * 50/100 = 43.1$ % for a grain-rich crop rotation on JB3, and $36.2 + 36.2 * 73.0/100 * 50/100 = 49.4$ % for a grain-rich crop rotation on JB6.

The magnitude of this “carry-over” effect of N fertilizer level is in concordance with winter wheat results from Thomsen et al. (2003), where a long-term previous fertilizer level difference of 78 kg N ha⁻¹ on clayey soil resulted in an extra harvest of approx. 10 kg N ha⁻¹, where the present coefficients also would predict 10 kg N ha⁻¹. Note though that these changes are so minute relative to the uncertainties associated with such field experiments, that this apparent concordance should not be overemphasized.

Calculating the soil N changes with C-TOOL, an additional 9.6 % are incorporated into the soil N pool by adding extra mineral N. This is done by taking the grain yield response (3rd order polynomial approximation, corrected for carry-over effect of the previous crop) at norm N fertilisation for respectively wheat and barley, and utilize the allometric functions for C crop distributions from Gyldenkærne et al. (2007). Hereby the residue increases by an infinitesimal small increase in N fertilisation with 50 % removal of straw can be calculated. The values are averages for wheat and barley on the respective soil types.

The above leads to the first set of marginal responses in Table A.14.

Table A.14.

The 10-year fate of a small change in mineral n application at normal fertilisation levels in a grain-rich crop rotation. Numbers for 100 years in parentheses (see text further below).

Fate of N	Partitioning on JB3 soil	Partitioning on JB6 soil
Ammonia volatilisation	2.0%	2.0%
Denitrification, N₂O (IPCC)	1.00% (1.07%)	1.00% (1.07%)
Denitrification, N₂O + NO_x (SimDen ratio)	3.0% (3.2%)	6.0% (6.4%)
Soil organic N change (C-TOOL)	9.6% (2.8%)	9.6% (2.7%)
Harvest (as explained in text)	43.1% (45.0%)	49.4% (51.9%)
Leaching, calculated as the remainder	41.3% (45.9%)	32.0% (35.9%)

When comparing with the quite similar table 21 in Petersen & Djuurhus (2004), the values for marginal leaching is higher in this table, compared to the 0.25 – 0.35 in Petersen & Djuurhus (2004). The lowest value is for sandy soils, and the highest for clay soils. These values are approximately the values obtained by using the NLES₃ N leaching model (Kristensen et al., 2003) though, whereas the present leaching is based on a mass conservation principle.

The other model, besides NLES₃, utilised in the final evaluation (Grant and Waagepetersen, 2003) of the “Vandmiljøplan II” (the Danish Action Plan on the Aquatic Environment II) is SKEP/Daisy (REF). This model gives a higher marginal response for mineral N of 0.59 on JB3 soil, whereas it gives a slightly lower response of 0.27 on JB6 soil (both from Knudsen and Østergard, 2005). Taking a crude average of the response for NLES₃ and SKEP/Daisy for JB3 and JB6 gives an approximate average marginal response of 0.37, which, although unintended, is identical to the average response the present approach yields.

The analogous N fate responses for pig and cattle slurry N may also be obtained.

First the ammonia and denitrification losses are taken from table A.17.

Thereafter the harvested N in bailed straw and grain is calculated by utilizing the substitution values of 0.75 and 0.7, for respectively pig and cattle slurry. As there for cattle slurry, after all gaseous losses, is 71.1 % (JB3) resp. 67.3 % (JB6) of the applied N left, this assumed utilization for plant uptake appears high relative to the sum of organic and mineral N present according to these estimates, *before* soil N incorporation. It falls out of the scope of this study to estimate possibly improved coefficients for crop availability though, so the present estimates are utilised.

The soil N changes for slurry amendment are calculated with the C-TOOL model.

Finally, the leaching response is calculated by the mass conservation principle.

Table A.15.

The 10-year fate of a small change in pig slurry n application at normal fertilisation levels in a grain-rich crop rotation. Numbers for 100 years in parentheses (see text further below).

Fate of N	Partitioning on JB3 soil	Partitioning on JB6 soil
Ammonia volatilisation	10.4.%	10.4 %
Denitrification, N₂O (IPCC)	1.00% (1.10%)	1.00% (1.11%)
Denitrification, N₂O + NO_x (SimDen ratio)	3.0% (3.3%)	6.0% (6.6%)
Soil organic N change (C-TOOL)	14.5% (4.1%)	15.3% (4.3%)
Harvest (as explained in text)	32.3% (35.2%)	37.1% (41.0%)
Leaching, calculated as the remainder	38.8% (45.9%)	30.3% (36.6%)

Table A.16.

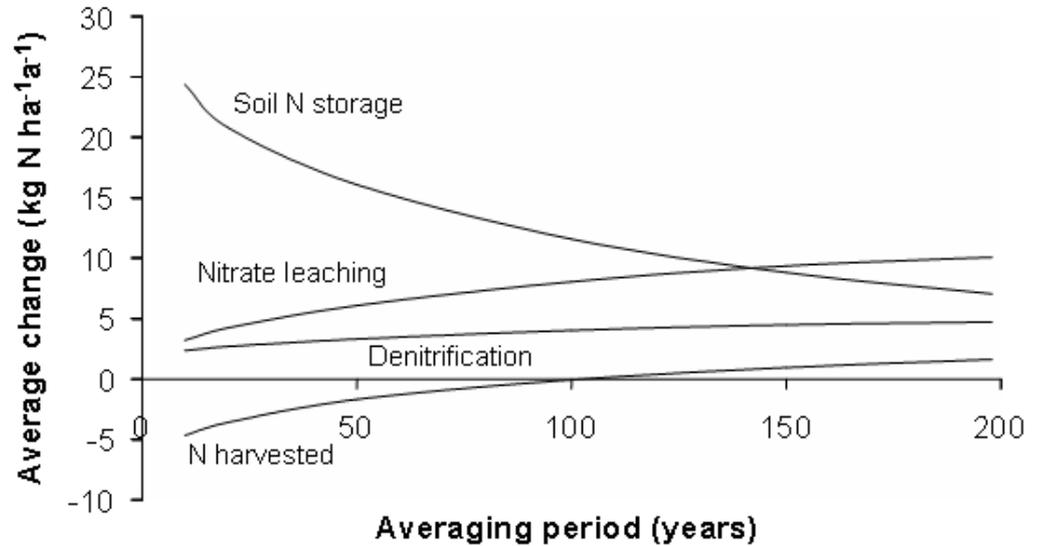
The 10-year fate of a small change in cattle slurry n application at normal fertilisation levels in a grain-rich crop rotation. Numbers for 100 years in parentheses (see text further below).

Fate of N	Partitioning on JB3 soil	Partitioning on JB6 soil
Ammonia volatilisation	12.9.%	12.9 %
Denitrification, N₂O (IPCC)	1.00% (1.13%)	1.00% (1.14%)
Denitrification, N₂O + NO_x (SimDen ratio)	3.0% (3.4%)	6.0% (6.8%)
Soil organic N change (C-TOOL)	18.5% (5.3%)	19.6% (5.5%)
Harvest (as explained in text)	30.2% (33.9%)	34.6% (39.6%)
Leaching, calculated as the remainder	34.4% (43.4%)	25.9% (33.9%)

One of the overlooked challenges of determining marginal responses is the significance of the considered time scale. When for instance adding extra slurry to the soil, with full substitution for the fertiliser value in terms of applied mineral N, the different fates of N will change radically over the decades, as figure A.3 exemplifies.

Figure A.3

Dependence of the average change in N partitioning on the averaging period, taken from Petersen et al. (2005). The curves represent the average annual difference from the onset of the simulation between continuous slurry application and mineral fertilisation, calculated with the FASSET (Berntsen et al., 2003) agroecosystem model..



Note that the changes in figure A.3. are estimated consequences of a lasting and big change, relative to the baseline scenario, whilst the present estimates are for a “one-event” extra addition of a minute amount of mineral or organic fertiliser. So the time-related changes in respectively figure A.3. and in the present study are not completely comparable.

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 by IPCC to be subject to denitrification, with the same factor as for N amendment.

The N for harvest from mineralization, relative to applied mineral N, is calculated with the same factors as utilized for constructing table A.14.

Subsequently, the new value for leaching may be calculated. This is done for the mineral N application, and the two slurry types.

The responses derived here are presumed well suited for the grain-rich crop rotation of the pig farm. It is also presumed that the responses are valid for the cattle farm crop composition, but the grass-clover mixture occurring here adds another level of complexity to the system and its responses. Unfortunately this is also a system which has been investigated less. So the coefficients are more uncertain for this crop composition.

A.5.6 Phosphorus leaching

The loss of phosphorous from fields is affected by complex dynamics influenced by the soil phosphorus levels, climate, topography, soil conditions, crop type and method of cultivation of the fields. Hence, there are tremendous variations in the loss of phosphorous from different fields (Poulsen and Rubæk, 2005). The routes for the agricultural phosphorous loss are many, such as erosion, surface runoff, leaching to drains, contribution from the surface-near groundwater etc. According to Poulsen and Rubæk (2005), erosion-based losses are just over 50% of the estimated total losses, and bank erosion is by far the largest individual contributor. Leaching from drained wetlands is another significant source.

Even though there is no clear connection between the input of phosphorous to fields and the leaching of phosphorous, a continued net input of surplus phosphorous to agricultural farming soil will - all things being equal - lead to increased risk of loss of phosphorus from the agricultural land (Poulsen and Rubæk, 2005). The loss of particle bound phosphorous by surface runoff and leaching to drains increases with increasing content of phosphorous in the soil. Moreover, the risk of leaching of dissolved phosphorous increases with increasing phosphorous saturation of the soil as the ability of the soil to retain the phosphorous decrease.

It should be emphasized that there is no linearity between the phosphorous added to a field and the leaching of phosphorous. Accordingly, the estimates in this study should only be seen as very rough estimates! Detailed modelling of the phosphorous leaching is beyond the scope and budget of this project.

Poulsen and Rubæk (2005) give some rough estimates for the leaching of agricultural phosphorus in Denmark (data for year 2000):

- The agricultural losses of phosphorous to the aquatic environment ranges between 690 and 1300 tons P per year depending on the method, the time-scale and the input data used according to the national monitoring programme, NOVA (Poulsen and Rubæk (2005) page 28).
- At the national level, phosphorus excretion in animal manure totalled 55000 tons P (year 2000 level) (Poulsen and Rubæk (2005) page 19)
- The input from mineral fertilisers was 17300 tons P per year (Poulsen and Rubæk (2005) page 19).
- Inputs from waste, incl. sewage sludge and atmospheric contribution were in the range of 5800 tons P per year (Poulsen and Rubæk (2005) page 19).

Based on data from Poulsen and Rubæk (2005), the leaching of phosphorous in Denmark corresponds to 1.2% of the P input to the field²¹. It should be emphasised that this should be regarded as a **very** rough estimate, and that Poulsen and Rubæk (2005) would probably not use their data for this calculation themselves, as the leaching of phosphorous is caused by years and years application of surplus phosphorus to the soil and not the consequence of the application one year. As the application of P to soil has been significantly higher during the last 50-60 years (Poulsen and Rubæk, 2005, page 35 figure 1.2), an excess amount of phosphorous has been build up in the soil, and the leaching is reflecting the current soil phosphorus levels rather than the input in one year. When taking this into account, the leaching of phosphorous is significantly lower than the 1.2% of the phosphorous input to agricultural soil. Accordingly, the 1.2% should be regarded as an estimate for the maximum.

Since 2000, the contribution of phosphorus from manure has been reduced significantly (Vinther and Poulsen, 2008). The yearly input from mineral fertilisers, organic waste and from animal feed (leading to P in manure) has decreased by 4000 tons P from 2001/2002 to 2007/2008 and the yearly output by plant products and animal products has increased by 1000 tons and 1500 tons, leading to a total decrease in the surplus P of 6500 tons. Even though the surplus phosphorus has decreased since 2000, the data from Poulsen and Rubæk (2005) has been used for estimating the relationship between the phosphorous applied to the field and the agricultural leaching of P, as newer data has not been available.

It could be discussed whether the leaching of phosphorus should be seen as a percentage of the total input of P to the field, or in relation to the surplus amount of P applied to field (i.e. the input of P minus the uptake of P by the plants). Ideally the P balances in this study should be based modelling of field balances including P added as manure, P added as mineral fertiliser and P removed with the crop harvested, as done for nitrogen leaching in section A.5.5, and in addition to this inclusion of modelling of soil phosphorus levels. However, it has not been possible to model the phosphorous leaching, as it is far more complicated than modelling of nitrogen (which is not simple either). As mentioned above, Poulsen and Rubæk (2005) describe the complexity of modelling P leaching.

Nielsen and Wenzel (2005) assume a leaching of phosphorous is in the order of 5% of the net surplus application, assuming that phosphorus spread with manure on farmland at farms with 1.4 livestock units²² per ha or more is on average in the order of 30 kg P per ha while the plant uptake is about 20 kg P per ha (Kronvang et al., 2001). The net surplus is then about 10 kg P per ha. Nielsen and Wenzel (2005) emphasize that it is a rough estimate and perform sensitivity analysis for a leaching of 0% and 100% of the net surplus.

²¹ The estimate is based on the data in Poulsen and Rubæk (2005, page 5 and page 14): The average leaching of P **from agriculture** is $(690 + 1300 \text{ tons P})/2 = 995 \text{ tons P}$ per year. The input of P **from agriculture** to fields is 55000 tons P from manure + 17300 tons P from mineral fertilisers + 5800 tons from sewage sludge and atmosphere = 78100 tons P. Leaching of P is then estimated to 1.2% of the total amount of P applied to the fields (i.e. 955 tons P / 78100 tons P input).

²² In Danish: Dyre-enhed (DE)

Dalgaard et al. (2006) assume that 2.9% of the farm gate P balance leached as phosphate.

If the modelling is based on the *net surplus* amount of phosphorous, it implies that *if* there is no surplus of P applied to the field, there will be no leaching of phosphorous. This is not necessarily true. The erosion based loss might occur and as long as the soil contains phosphorous, there will probably be a small loss, even if P is not applied to the field in excess amounts. When watching the leaching of N as a function of the amount of applied N in figure A.2 in the beginning of section A.5.5 for nitrogen leaching, it can be seen that there is a small leaching of N regardless of the amount of N applied (for small amounts of applied N). For higher amounts of applied N, the N leaching increases with increasing amounts of applied N. The leaching of P might follow a similar pattern.

In this study, the EDIP 2003 approach for phosphorous leaching has been applied (Hauschild and Potting, 2005). It builds on a simple linear assumption, which will most likely not be applicable for all levels of application of P. However, as the application of phosphorous to field is the same for the reference system and the new technologies in this study, it has no consequences for the comparisons (however, this only applies for the new technologies in this study). For future assessments of new slurry management technologies, where the amount of P applied to field is changed, sensitivity analysis should be carried out, applying different approaches for phosphorous leaching modelling – based on the total input of P to field (as done in this study) and based on the *surplus* amount of P applied to field.

According to Hauschild and Potting (2005, Annex 6.3), 10% of the P applied to field has the possibility of leaching (this is the amount of P that should be entered into the life cycle modelling in SimaPro). Of this, 6% actually reach the aquatic recipients according to the model used by Hauschild and Potting (2005). As a result, 0.6% of the amounts of P applied to field actually reach aquatic recipients according to the EDIP 2003 method. When keeping the huge uncertainty on the estimates in mind, the estimate by Hauschild and Potting (2005) (i.e. that 0.6% of the P input to field reach aquatic recipients) is at the same level as the estimates for the phosphorous leaching to the aquatic environment based on Poulsen and Rubæk (2005) (1.2% as mentioned above).

It is assumed that the leaching of P from mineral P fertilisers is the same as leaching of P from slurry.

The amount of P applied to field is 1.04 kg per 1000 kg pig slurry ex storage and 0.98 kg per 1000 kg dairy cow slurry ex storage, see table A.1 and A.2. 10% of this has the potential of leaching.

A.5.7 Summary of the Life Cycle Inventory Data

Table A.17.

Life cycle data for application of slurry and field processes (reference scenario). All data expressed per 1000 kg of slurry ex outdoor storage.

	Fattening pig slurry	Dairy cow slurry	Comments
Input			
Slurry "ex storage"	1000 kg	1000 kg	Slurry 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 A.6.1.	The fertiliser value of this slurry represents the amount of N, P and K available for the crops. The fertiliser replacement value is described in section A.6.1.
Energy consumption			
Diesel for slurry	0.4 litres of diesel	0.4 litres of diesel	The amount of diesel based on Kjelddal (2009). Modelled by the use of data from the Ecoinvent process: "Slurry spreading, by vacuum tanker".
Emissions to air			
Carbon dioxide (CO ₂)			Modelled by C-TOOL (Gyldenkærne et al, 2007). 10 year value (100 year in parenthesis)
Soil JB3	81.6 (99.8) kg	126.4 (154.5) kg	
Soil JB6	80.2 (99.4) kg	124.2 (153.8) kg	
Methane (CH ₄)	Negligible	Negligible	The CH ₄ emission on the field is 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	0.02 kg	NH ₃ emissions during application: 0.5% of NH ₄ ⁺ -N "ex storage", see table A.1 and A.2 and text below. Hansen et al. (2008).
Ammonia (NH ₃ -N) in period after application	0.48 kg	0.73 kg	NH ₃ emissions in the period after application are based on Hansen et al. (2008) and the current slurry distribution in the crop rotation, see text.
Direct emissions of Nitrous oxide (N ₂ O-N)	0.05 kg [0.015-0.15]	0.06 kg [0.018-0.18]	0.01 [0.003 - 0.03] kg N ₂ O-N per kg N "ex storage" for application of animal wastes to soil, based on IPCC (2006, table 11.1).
Indirect emissions of Nitrous oxide (N ₂ O-N)	0.005 kg	0.006 kg	Indirect emissions due to emissions of ammonia and NO _x : 0.01 kg N ₂ O-N per kg (NH ₃ -N + NO _x -N) volatilised (IPCC, 2006)
Soil JB3	0.014 kg	0.016 kg	Indirect emissions due to nitrate leaching: 0.0075 kg N ₂ O-N per kg N leaching (IPCC, 2006).
Soil JB6	0.011 kg	0.0125 kg	
Nitrogen oxides (NO _x -N)	0.005 kg	0.006 kg	NO _x -N = 0.1 * N ₂ O-N according to Nemecek and Kägi (2007)
Nitrogen (N ₂ -N)			Estimated from the SimDen model ratios between N ₂ O and N ₂ by Vinther (2005), see text.
Soil JB3	0.15 kg	0.18 kg	
Soil JB6	0.30 kg	0.36 kg	
Discharges to soil			
Nitrate leaching			Estimated from N partitioning tables A.15 and A.16. 10 year values, numbers in parenthesis are 100 year values
Soil JB3	1.91 (2.12) kg N	2.16 (2.59) kg N	
Soil JB6	1.50 (1.67) kg N	1.67 (2.04) kg N	
Phosphate leaching	0.104 kg P	0.098 kg P	10% of the P applied to field (Hauschild and Potting, 2005 – only 6% of this reach the aquatic environment, see text).
Copper (Cu)	0.0276 kg	0.0116 kg	See table A.1 and A.2
Zinc (Zn)	0.0824 kg	0.0224 kg	See table A.1 and A.2

A.6 Avoided mineral fertilisers

The application of N, P and K in the slurry replaces mineral fertilisers. The replaced production and application of mineral fertilisers are subtracted from the reference scenario. When taking the consequential, marginal approach into consideration, the production of mineral N fertilisers that are affected by the slurry application should be identified, i.e. the production of mineral fertiliser that will be affected when the N in pig slurry and cattle slurry is used more efficiently. Furthermore, the affected production of P and K fertiliser should be identified.

A.6.1 Amount of replaced mineral fertilisers

In Denmark, the farmers' use of N fertilisers is restricted by Danish law (Gødskningsbekendtgørelsen, 2008, and Gødskningsloven, 2006). It means that the amount of N fertiliser farmers are allowed to bring out has an upper ceiling, both as mineral fertiliser and animal slurry. The farmers have to make accounts on their fertiliser use, and they have to include a fixed amount of the N content of the animal slurry in their fertiliser accounts. The substitution requirements in the Danish law are 75% for pig slurry and 70% for cattle slurry. The requirement means, that when the farmer brings out 100 kg total N in pig slurry, he has to include it in the fertiliser account corresponding to 75 kg N in mineral fertiliser which means that the farmer has to reduce the consumption of mineral N fertiliser by 75 kg. Accordingly, it is assumed that 100 kg N added in the pig slurry replaces 75 kg N in mineral fertiliser. 100 kg N added in the cattle slurry replace 70 kg N in mineral fertiliser.

As the farmer calculates the amount of N according to the Norm Data, the "avoided mineral N fertiliser" is calculated in accordance with the N ex storage from the Norm data, i.e. without the loss of N due to N_2O , NO_x and N_2 emissions. These are shown in table A.1 for pig slurry and table A.2 for dairy cow slurry. Accordingly, for pig slurry the avoided mineral N fertiliser is calculated as: 75% of 5.00 kg N ex storage = 3.75 kg N (i.e. not calculated as 75% of the calculated N content in this study as 4.80 kg N, see table A.1). For dairy cow slurry the avoided N in mineral fertiliser corresponds to 70% of 6.02 kg N (Norm Data ex storage) = 4.21 kg N. The avoided N in mineral fertiliser is higher when calculated according to the Norm Data ex storage than if calculated as the percentage of the data in this study. However, when modelling the consequences of what the farmer does, it is the Norm Data the farmer uses for his N accounts.

For P and K the conditions are different.

The **fertiliser value** of P and K applied in slurry is generally assumed to have the same value as in mineral fertilisers (i.e. that 1 kg P in slurry has the same plant availability as 1 kg P in mineral fertilisers). This assumption is also used by e.g. Thyø and Wenzel (2007) and Börjesson and Berglund (2007). Poulsen and Rubæk (2005, page 26) support this assumption for phosphorous "***In terms of plant nutrition, phosphorus in readily soluble mineral fertilizer and animal manure is considered of equal value. It appears though that animal manure phosphorus is more mobile and is more easily transported to deeper soil layers than mineral fertilizer phosphorus***". Sommer et al. (2008) mention

that the immediate availability of P in slurry may be somewhat lower than for mineral fertilisers.

Nevertheless, the assumption that the P and K fertiliser **value** is the same for slurry and mineral fertilisers does not necessarily mean that the **replacement** is carried out 1:1. In consequential life cycle assessments, the key issue is to identify the consequences in **real life**. In this case, the question is: “What would the consequence be if the farmer did not apply slurry and thereby P and K to the field?”. The answer is that he would apply mineral fertilisers instead. However, the application of slurry to field leads to excess amounts of P and K when the slurry is applied in accordance with the requirements set by Danish law (Miljøministeriet, 2006). If applying mineral fertilisers instead of slurry, he would probably not apply P and K in excess amounts. Poulsen and Rubæk (2005) assumes that mineral P fertiliser is applied in amounts that are adjusted to the soil phosphorus levels and the needs of the crop²³. Accordingly, it is assumed that P and K would not be applied in excess amounts if mineral fertilisers were used, and as a result, P and K in slurry does not replace mineral fertiliser 1:1.

In this study, it is assumed that the amount of P and K applied as mineral fertilisers is based on measurements of the needs of the crop. It is assumed that this does not lead to application of P and K in excess amounts. Accordingly, only part of the P and K applied in the slurry actually replace mineral fertilisers.

The calculations of the replacement of P and K mineral fertilisers is based on the requirements set by Danish Law (Miljøministeriet, 2006) and the recommendations for fertilising crops by Plantedirektoratet (2008). The amount of slurry applied to the field is calculated in accordance with Danish Law (Miljøministeriet, 2006), i.e. 1.4 livestock units²⁴ per ha for pigs and 1.7 livestock units per ha for cattle. There is 0.85 dairy cow per livestock unit (heavy race) and 35 fattening pigs per livestock unit (Miljøministeriet, 2006). Note that the amount of animals per livestock units were defined in accordance with the Norm Data from 2000 for fattening pigs and 1999 for dairy cows and as the Norm data (N ex storage per animal) has changed, 1 livestock unit does not correspond to 100 kg N ex storage anymore, even though this was the original definition. The amount of slurry and content of N, P and K is given by DJF (2008), which is in accordance with the guidelines from Plantedirektoratet (2008).

For fattening pigs, the amount of slurry applied to 1 ha is: 1.4 livestock units per ha * 35 fattening pigs per livestock unit * 0.52 tonnes slurry per pig (ex storage) = 25.48 tonnes pig slurry per ha. This amount of slurry contains:

- 5.00 kg N per tonnes slurry * 25.48 tonnes slurry = 127.4 kg N per ha
- 1.04 kg P per tonnes slurry * 25.48 tonnes slurry = 26.50 kg P per ha
- 2.60 kg K per tonnes slurry * 25.48 tonnes slurry = 66.25 kg K per ha

²³ Poulsen and Rubæk (2005, page 24) assumes that if P in the feed is reduced, it will lead to a reduced application of P in animal manure, leading to an overall reduction “... **assuming that a reduction in mineral feed phosphates is not counteracted by an increase in the use of mineral fertilizer phosphate**” and Poulsen and Rubæk (2005, page 159) “**Handelsgødningsfosfor tildeles typisk årligt i mængder, der er afpasset efter jordens fosforstatus og afgrødens behov**”

²⁴ In Danish: Dyre-enhed, DE

For dairy cows, the amount of slurry applied to 1 ha is: 1.7 livestock units per ha * 0.85 dairy cows per livestock unit * 21.3 tonnes slurry per dairy cow (ex storage) = 30.78 tonnes dairy cow slurry per ha. This amount of slurry contains:

- 6.02 kg N per tonnes slurry * 30.78 tonnes slurry = 185.3 kg N per ha
- 0.98 kg P per tonnes slurry * 30.78 tonnes slurry = 30.16 kg P per ha
- 5.65 kg K per tonnes slurry * 30.78 tonnes slurry = 173.91 kg K per ha

The amounts of P and K recommended to each crop type is based on the recommendations given by Plantedirektoratet (2008, table 1), calculated in accordance with the crop rotation given in section 3.1.

The 6 years crop rotation for pig slurry is defined in section 3.1 to: winter barley – winter rape – winter wheat – winter wheat – spring barley with catch crop – spring barley. With this crop rotation, the recommended amounts of P and K are 21.5 kg P per ha and 64 kg K per ha (average, weighted with regard of the crop rotation).

The 5 years crop rotation for dairy cow slurry is defined in section 3.1 to: whole crop silage – grass clover mixture – grass clover mixture – spring barley with catch crop – spring barley. With this crop rotation, the recommended amounts of P and K are 27.8 kg P per ha and 125.8 kg K per ha (average, weighted with regard of the crop rotation).

In addition to the P and K in the slurry, mineral fertilisers might be added by the farmer. However, this is not caused by the slurry management and is not relevant for the goal of this study. If the farmer adds more mineral P and K than the recommended amounts, they are either “excess amounts” or due to that the P or K from the slurry is not available for the crop. It is beyond the scope of this study to model the fate and availability of P and K at the field.

The excess amount of P and K and the percentage of the P and K in the slurry that actually replace mineral fertilisers are calculated:

For fattening pig slurry:

- 26.50 kg P per ha is added in the slurry, 21.5 kg P per ha is recommended, excess amount is 5 kg P per ha, corresponding to that only 81.1% of the P in the slurry replace mineral fertilisers in the reference scenario.
- 66.25 kg K per ha is added in the slurry, 64 kg K per ha is recommended, excess amount is 2.25 kg K per ha, corresponding to that only 96.6% of the K in the slurry replace mineral fertilisers in the reference scenario.

For dairy cow slurry:

- 30.16 kg P per ha is added in the slurry, 27.8 kg P per ha is recommended, excess amount is 2.36 kg P per ha, corresponding to that 92.2% of the P in the slurry replace mineral fertilisers in the reference scenario.
- 173.91 kg K per ha is added in the slurry, 125.8 kg K per ha is recommended, excess amount is 48.11 kg K per ha, corresponding to that only 72.3% of the K in the slurry replace mineral fertilisers in the reference scenario.

Accordingly, the replaced amounts of mineral fertilisers for pig slurry in the reference system are calculated relative to the “functional unit” i.e. 1000 kg slurry ex animal:

- Mineral N fertiliser: 5.00 kg N per 1000 kg slurry ex storage [the value given by the Danish Norm Data, as explained in table A.1] * 1086 kg slurry ex storage per 1000 kg slurry ex animal * 75% [the replacement value for pig slurry according to (Gødskningsbekendtgørelsen, 2008)] = 4.073 kg mineral N fertiliser
- Mineral P fertiliser: 1.04 kg P per 1000 kg slurry ex storage * 1086 kg slurry ex storage per 1000 kg slurry ex animal * 81.1% = 0.916 kg P
- Mineral K fertiliser: 2.60 kg K per 1000 kg slurry ex storage * 1086 kg slurry ex storage per 1000 kg slurry ex animal * 96.6% = 2.73 kg K

The replaced amounts of mineral fertilisers for dairy slurry in the reference system are:

- Mineral N fertiliser: 6.02 kg N per 1000 kg slurry ex storage [the value given by the Danish Norm Data, as explained in table A.2] * 1044 kg slurry ex storage per 1000 kg slurry ex animal * 70% [the replacement value for cattle slurry according to (Gødskningsbekendtgørelsen, 2008)] = 4.399 kg mineral N fertiliser
- Mineral P fertiliser: 0.98kg P per 1000 kg slurry ex storage * 1044 kg slurry ex storage per 1000 kg slurry ex animal * 92.2% = 0.943 kg P
- Mineral K fertiliser: 5.65kg K per 1000 kg slurry ex storage * 1044 kg slurry ex storage per 1000 kg slurry ex animal *72.3% = 4.26 kg K

A.6.2 Market considerations for mineral fertilisers

Mineral fertilisers are traded on markets. According to the consequential methodology, the fertilizers (and the technology used to produce them) affected by a change of the slurry management in Denmark will only be the marginal ones. According to Weidema (2003), the technology with the lowest long-term production cost is the one that is likely to be implemented in case of increasing demand and would therefore be the marginal. Oppositely, if the demand trend is decreasing, the least competitive technology is the most likely to be phased out and would represent the marginal in that case.

According to this methodology, it should therefore be known if the demand for mineral fertilisers is an increasing or decreasing trend. This depends on the market considered, i.e. if Europe is regarded as a closed market or whether if it is regarded as an open market. It is however beyond the frameworks of this study to conduct a market analysis for mineral fertilisers and to collect data for old and modern technologies for the production of various types of mineral fertilisers. Accordingly, a pragmatic approach has been taken.

First, the fertiliser's data available in the Ecoinvent database were taken into account. A variety of fertilizers data is available in this database, as shown below :

N-fertilisers:	Ammonium nitrate Ammonium sulphate (N and S) Calcium ammonium nitrate Calcium nitrate Urea ammonium nitrate Urea
P-fertilisers:	Single superphosphate Triple superphosphate
K-fertilisers:	Potassium chloride Potassium sulphate (K and S)
Mixed N P K fertilisers:	Ammonium nitrate phosphate (N and P) Diammonium phosphate (N and P) Monoammonium phosphate (N and P) Potassium nitrate (N and K)

It can be noticed from this overview of the available data in EcoInvent as regarding fertilizers that data are presented for both mixed and non mixed fertilizers. For simplification and due to lack of data in the statistics, mixed fertilisers (i.e. fertilisers including a combination of N and P or N, P and K) have not been used as the marginal fertiliser in this study. In fact, the data by Plantedirektoratet (2008) are not detailed enough for estimating the combination of mixed fertilisers as the P and K content are not stated for the mixed mineral fertilisers.

As a second step of the pragmatic approach adopted, the market context for mineral fertilisers was briefly examined, for both N, P and K fertilisers. The total sale of mineral fertilisers in Denmark is slightly decreasing. However, the worldwide demand for fertilisers is increasing. Alley and Spargo (2007) states: ***“Growth in the economies of China and India, in particular, as well as other countries has created a greater worldwide demand for fertilisers, and increased use of corn for ethanol production is increasing fertiliser demand in the United States due to expected increases in corn acres. World production capacity for N and P fertilisers is slightly greater than demand while potash capacity is significantly greater than demand, but production has been constrained by several factors in recent years. Adequate supplies of fertilisers appear to be available in the world market, but logistical challenges exist for nitrogen and potash in particular.”***

According to table 2 in Alley and Spargo (2007) the worldwide consumption of fertilisers have been increasing significantly from 2004-2007 for N-fertilisers, and P-fertilisers as well as for K-fertilisers.

A.6.3 Marginal N fertiliser

For N fertilisers, the main consumption in Denmark is “N fertilisers mixed with sulphur” and NPK, NP or NK fertilisers according to the statistics by Plantedirektoratet (2008). However, as mentioned above, since the composition of the mixed N fertilisers is not stated in the statistics, it is not possible to use these for the modelling. According to the statistics by IFA (2008), Plantedirektoratet (2008) and Nielsen et al. (2008), the most commonly used non-mixed N fertiliser is calcium ammonium nitrate. The Danish consumption of calcium ammonium nitrate has been decreasing in the period of 1998-2006 (IFA, 2008 and Plantedirektoratet, 2008), which is, however, the case for most of the N fertilisers but ammonium sulphate, “liquid fertilisers” and urea. Alley and Spargo (2007) states that urea is the most widely traded N source in the world. However, it is not very used in Denmark. When analysing the production of calcium ammonium nitrate in the Ecoinvent Database, it is very similar to the production of ammonium nitrate plus limestone (for the calcium). Accordingly, ammonium nitrate is assumed to be the marginal N fertiliser in this study. For the sensitivity analysis, ammonium sulphate has been used as the environmental profile for this is rather different from the impacts of calcium ammonium nitrate in order to assess the significance of this for the overall results.

Accordingly, in this study the process “Ammonium nitrate, as N, at regional storehouse/RER U” from Ecoinvent database has been used. However, the Ecoinvent data has been modified slightly. According to the background documentation for this process (Nemecek and Kägi, 2007), the emission of N_2O from the processing of nitric acid is based on literature data from 1997, which means that the data are probably more than 10 years old. As the N_2O emission from this process has great significant for the overall results of the Life Cycle Assessment in this report, newer data for the N_2O emissions has been applied. According to the BREF document for production of nitric acid, the emission level for N_2O for new plants is 0.12 – 0.6 kg/tonne 100 % HNO_3 and 0.12 – 1.85 kg/tonne 100 % HNO_3 for existing plants (European Commission, 2007). However, the BREF document states: “Industry and one Member State claim that the BAT range should include 2.5 kg N_2O /tonne 100 % HNO_3 for existing plants.” (European Commission (2007), section 3.5, page 140). In the Ecoinvent database, the N_2O emission for the production of nitric acid corresponds to 8.39 kg N_2O /tonne 100 % HNO_3 . The N_2O emission has been modified to 2.5 kg N_2O /tonne 100 % HNO_3 in this study.

The application of mineral fertilisers are included by the Ecoinvent process “Fertilising, by broadcaster”. Emissions from the diesel consumption by the tractor are included in the Ecoinvent process “Fertilising, by broadcaster”. The diesel consumption in the Ecoinvent data corresponds to a consumption of 6.3 litres of diesel per ha. According to Dalgaard et al. (2002) the energy consumption for application of mineral fertiliser is 2 litres of diesel per ha. In the calculations, the energy consumption by Dalgaard et al. (2002) has been used, modelled by the relative ratio using the Ecoinvent data. In the calculations it is assumed that there is applied 30 tons slurry per ha (i.e. 1/30 of ha per 1000 kg slurry). Accordingly, there is avoided application of mineral fertilisers on an area of 1/30 ha per 1000 kg slurry. A rough estimate is 0.007 litres of diesel per kg fertiliser (assuming that all three fertilisers are applied at the same time).

The application of N fertiliser will lead to emissions of NH₃, which means that by avoiding application of N fertiliser also avoid NH₃ emissions. Nielsen et al. (2008b) gives a table of the NH₃ emission factors for mineral fertilisers (For calcium ammonium nitrate, the NH₃-N emission factor is 2% of the added N (Nielsen et al. (2008), Annex C, table 2C.6) and European Environment Agency (2007, page B1010-12 table 4.1).

The N₂O emission factor for mineral N fertilisers is 0.01 kg N₂O -N/kg N for application of mineral fertilisers to soil, based on IPCC (2006, table 11.1).

In addition, the indirect N₂O emission have been included in accordance with the IPCC (2006) guidelines, i.e. 0.01 kg N₂O-N per kg (NH₃-N + NO_x-N volatilised) (IPCC, 2006, table 11.3).

For NO emissions from N fertilisers, the emission factor recommended by the European Environment Agency (2007) has been applied: 0.7 % NO-N emissions related to the input of mineral fertiliser N.

A.6.4 Marginal P fertiliser

For P fertilisers, the Ecoinvent database only contains two phosphorous fertilisers that are not “mixed” with either N or K (As described above, it is preferable to model the avoided fertiliser production with non-mixed fertilisers (i.e. not NPK fertilisers, or NP fertilisers), if possible, in order to avoid making a “branch” of avoided processes influencing on each other):

- Single superphosphate, as P₂O₅, at regional storehouse/RER U
- Triple superphosphate, as P₂O₅, at regional storehouse/RER U

It is assumed that the avoided P fertiliser is Triple superphosphate. According to Broadley et al. (2006) single superphosphate has generally been replaced by triple superphosphate (at least in the UK). According to the statistics by Plantedirektoratet (2008), triple superphosphate is more commonly used than single superphosphate. According to the statistics by Plantedirektoratet (2008) it seems that the consumption of triple superphosphate as well as the consumption of single superphosphate has been decreasing since 2001 (however, the two types have been aggregated into one category since 2004 which makes it difficult to distinguish the marked trend for the two types). A sensitivity analysis for this assumption has been carried out as the environmental impacts of producing triple superphosphate is only 65-80% of the environmental impacts of producing single superphosphate according to a screening performed in SimaPro. In this study, the Ecoinvent process “Triple superphosphate, as P₂O₅, at regional storehouse/RER U” has been used. 1 kg P corresponds to 2.291 kg P₂O₅²⁵

According to the background documentation for the Ecoinvent database (Althaus et al., 2007), triple superphosphate is produced from phosphoric acid and phosphate rock. The production of phosphoric acid gives large amounts of phosphogypsum, which is an environmental challenge. The largest productions of phosphoric acid are in U.S. (29%) and Morocco

²⁵ 1 kg P = (2 * 30.97376 g/mol + 5 * 15.9994 g/mol) / (2 * 30.97376 g/mol) kg P₂O₅ = 2.291 kg P₂O₅

(17%). There are significant differences between the productions and discharges from the U.S phosphoric acid plants and the Morocco plants. In the U.S., the phosphogypsum is discharged from a filter, pumped to decantation basins where the gypsum settles before being recycled. No direct water discharge is assumed due to the closed water circuit. A leaching of 1% is assumed due to rain falling onto the stack area causing leaching into the aquifer. Phosphoric acid plants in Morocco dispose the phosphogypsum directly to the sea where it dissolves, and accordingly, all the phosphogypsum is calculated as short-term emissions to seawater (Althaus et al. (2007) and Anwar and Wissa (unknown year)).

It has not been possible to identify which type of phosphoric acid plant that is the marginal plant. However, in Europe, the emission of phosphogypsum to seawater is no longer accepted in Europe (European Commission, 2007, page 247). In this report, the U.S. phosphoric acid plant is used for the “basic calculation” as this reflects the European production better than the production in Morocco. The Morocco phosphoric acid plant is used for the sensitivity analysis. The environmental profile of the two productions are very similar but for the eutrophication (P) caused by the leaching of phosphogypsum in Morocco, which cause a contribution to “Eutrophication (P)” that is approximately 8.6 times higher for the production in Morocco.

A.6.5 Marginal K fertiliser

The potassium fertiliser in this study is modeled by the use of the Ecoinvent process “Potassium chloride, as K₂O, at regional storehouse/RER U”. According to the statistics by Plantedirektoratet (2008), potassium is most commonly applied in mixed mineral fertilisers combined with N, however, it has not been possible to include this due to a lack of data as described above. According to the statistics by IFA(2008) and Plantedirektoratet (2008) potassium chloride is commonly used in Denmark. Plantedirektoratet (2008) assess the yearly consumption of potassium chloride, and there are no data for potassium sulphate. The consumption of potassium chloride in Denmark is slightly fluctuating without a clear increase or decrease. 1 kg K corresponds to 1.205 kg K₂O²⁶.

A.6.6 Summary of the Life Cycle Inventory Data

The Life Cycle Inventory Data for application of mineral fertilisers are shown in table A.18. The values in the table are positive; however, when the processes are subtracted from the system, they will lead to a “negative contribution” as the emissions are avoided.

²⁶ 1 kg K corresponds to $(2 \cdot 39.0983 \text{ g/mol} + 15.9994 \text{ g/mol}) / (2 \cdot 39.0983 \text{ g/mol}) = 1.205 \text{ kg K}_2\text{O}$.

Table A.18.

Life cycle data for application of mineral fertiliser (reference scenario). All data per 1 kg of mineral fertiliser applied.

	N fertiliser	P fertiliser	K fertiliser	Comments
Input				
N mineral fertiliser	1 kg N			Ecoinvent process: 1 kg Ammonium nitrate, as N, at regional storehouse/RER U
P mineral fertiliser		1 kg P		Ecoinvent process: 2.291 kg "Triple superphosphate, as P ₂ O ₅ , at regional storehouse/RER U"
K mineral fertiliser			1 kg K	Ecoinvent process: 1.205 kg "Potassium chloride, as K ₂ O, at regional storehouse/RER U".
Output				
	1 kg N	1 kg P	1 kg K	Fertiliser value
Energy consumption				
Diesel for spreading of mineral fertiliser	0.007 litres of diesel per kg N	0.007 litres of diesel per kg P	0.007 litres of diesel per kg K	Modelled by use of the Ecoinvent process "Fertilising, by broadcaster"
Emissions to air				
Carbon dioxide (CO ₂), JB3 JB6	-3.52kg -3.52 kg	None	None	This is the equivalent of the extra soil C storage (10 years) that the extra N gives rise to, through more residues from a larger crop (C-TOOL)
Ammonia (NH ₃ -N)	0.02 kg	None	None	2% of N content
Direct emissions of Nitrous oxide (N ₂ O-N)	0.01 kg [0.004-0.05 kg]	None	None	1% of N content (IPPC, 2006, table 11.1).
Indirect emissions of Nitrous oxide (N ₂ O-N)	0.0002 kg	None	None	Indirect emissions due to emissions of ammonia and NO _x : 0.01 kg N ₂ O-N per kg (NH ₃ -N + NO _x -N) volatilised (IPCC, 2006)
Soil JB3 Soil JB6	0.0031 kg 0.0024 kg			Indirect emissions due to nitrate leaching: 0.0075 kg N ₂ O-N per kg N leaching (IPCC, 2006).
Nitrogen oxides (NO _x -N)	0.001 kg	None	None	NO _x -N = 0.1 * N ₂ O-N according to Nemecek and Kägi (2007)
Nitrogen (N ₂ -N) Soil JB3 Soil JB6	0.03 kg 0.06 kg	None	None	Estimated from the SimDen model ratios between N ₂ O and N ₂ by Vinther (2005), see text.
Discharges to soil				
Nitrate leaching Soil JB3 Soil JB6	0.413 (0.459) kg N 0.32 (0.359) kg N	None	None	From table A.14. 10 year values, numbers in parenthesis are 100 year values
Phosphate leaching	None	0.1 kg P	None	10% of the P applied to field (Hauschild and Potting, 2005 – only 6% of this reach the aquatic environment, see section A.5.6).

Annex B. Acidification of slurry – Life Cycle Inventory data

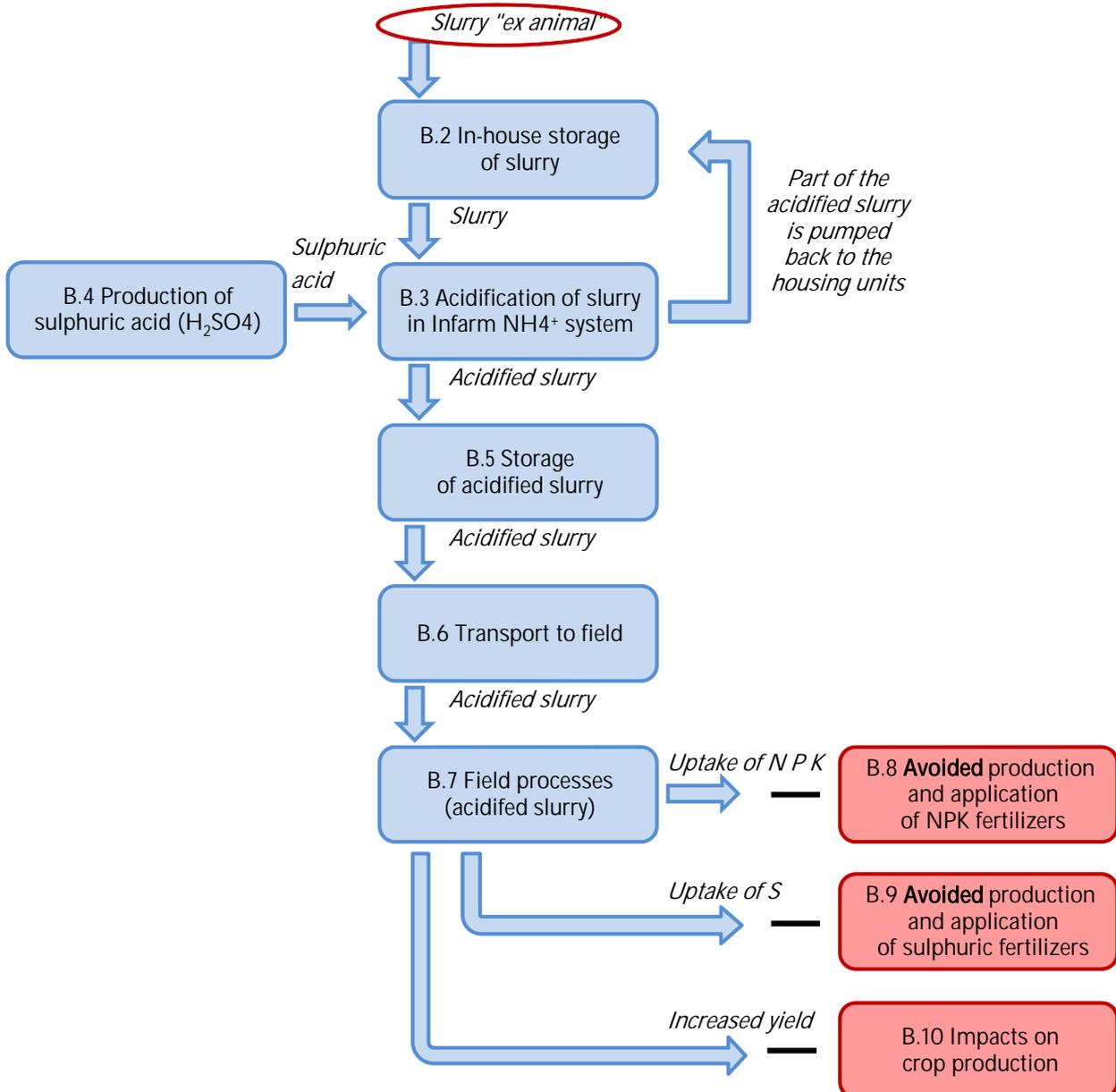
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B.1 System description

This appendix contains Life Cycle Inventory data for the acidification of slurry. The slurry is acidified by the addition of sulphuric acid (H_2SO_4). The sulphuric acid reduces the pH and the chemical equilibrium between ammonium (NH_4^+) and ammonia (NH_3) is changed which means that it is primarily in the form of ammonium (NH_4^+). As only ammonia (NH_3) evaporates, the pH of the slurry is a determining factor for the amount of nitrogen / ammonia that volatilize in the housing system, during storage and during application to fields. Moreover, acidification of the slurry has significance for other factors that will be described in this Annex. For example the use of sulphuric acid for the acidification might be an advantage as it adds sulphur to the field which has a fertilizer effect.

The system for acidification of slurry is shown in figure B.1.

Figure B.1: Flow diagram for the scenario for acidification of slurry.



B.2 In-house storage of acidified slurry

The main part of the acidified slurry is pumped back into the housing units, and this changes the emissions from the slurry in the housing. The Life Cycle Inventory data for the in-house storage of acidified slurry are shown in table B.1.

The energy consumption for the acidification system is included under “Acidification of slurry in the Infarm NH₄⁺ system” in section B.3 below.

Ottosen et al. (2009) investigated the microbial activity in acidified pig slurry. They found that the microbial activity, expressed as oxygen consumption, sulphate reduction and methanogenesis, was greatly reduced in acidified slurry. They state that the implications may be reduced emissions of hydrogen sulphide and methane, but increased volatilization of fatty acids.

Measurements by Dansk Landbrugsrådgivning (2004c) on cattle slurry indicate the same trend. Based on their 6 measurements (2 for non-treated slurry, 4 for acidified slurry) it can be calculated that acidification reduce the methane emissions by 32% [7-49%] and the direct nitrous oxide emissions by 83% [58-99%]. It should be emphasized that the room temperature is not the same for all the measurements and that the room temperature is significant for the microbial activity and hence the emissions. Furthermore, 6 measurements are not enough for statistical analysis, which is also emphasised by the authors of the report¹. As it has not been possible to identify more studies covering the influence of acidification of slurry on the methane or the nitrous oxide emissions, the data from Dansk Landbrugsrådgivning (2004c) have been used, well aware that it should be regarded with care. The same estimate has been used for pig slurry. The significance is discussed under sensitivity analysis.

No data have been found for the carbon dioxide emissions. As methane is a much stronger greenhouse gas than carbon dioxide, the carbon dioxide emissions are relatively unimportant for the total contributions from the housing units. It has been assumed that the carbon dioxide emissions are reduced by the same factor as the methane emissions.

Under the acidification process the carbonate balance is affected by the low pH in the slurry, forcing the carbonate into free CO₂. This might cause a higher emission of the CO₂ during the acidification process and in the housing units. The release of CO₂ is also due to the stripping caused by the aeration of the slurry. The aspect needs further investigation. However, it is assumed that this aspect does not influence the overall conclusions of the life cycle assessment, as it supposed that the **production** of CO₂ by the bioprocesses in the slurry is not affected, only the **release** of the CO₂ contained in the slurry, and as it is assumed that this CO₂ would be released at a later stage in the life cycle of the slurry (e.g. at the field). In conclusion, it is assumed that the total amounts of CO₂ in the entire life cycle are not affected.

¹ The very first sentence in the conclusion regarding methane is: ”På baggrund af de få målinger af metan er det ikke muligt at afgøre, om der er forskel mellem de undersøgte systemer.” (Dansk Landbrugsrådgivning (2004c), page 24).

The ammonia emissions from acidified slurry in the housing units are reduced by 70% for pig slurry compared to untreated slurry (BAT, 2009a and Dansk Landbrugsrådgivning (2004a) (BAT byggeblad 107.04-52) and Kai et al. (2007). For cattle slurry, the ammonia emissions are reduced with 50% (Dansk Landbrugsrådgivning (2004b) (BAT byggeblad 106.04-56)).

The emission of nitrogen monoxide (NO-N) is assumed to be at the same level as the direct N₂O-N emissions (Dämmgen and Hutchings, 2008), see description in Annex A.

The emission of Nitrogen (N₂-N) is assumed to be three times as high as the direct N₂O-N emissions (Dämmgen and Hutchings, 2008), see description in Annex A.

Table B.1.

Life cycle Inventory data for storage of acidified slurry in the housing units (scenario F).
All data per 1000 kg of slurry "ex animal".

	Fattening pig slurry	Dairy cow slurry	Comments
Input			
Slurry "ex animal"	1000 kg	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	1000 kg	Mass balances, see table B.4.
Energy consumption			
	Not included here	Not included here	The energy consumption for the acidification system is included under "Acidification of slurry in the Infarm NH ₄ ⁺ system" in section B.3 below.
Emissions to air			
Carbon dioxide (CO ₂)	2.34 kg	7.7 kg	No data is available. Estimate based on the same reduction factor as methane (32%), see below.
Methane (CH ₄)	2.2 kg [1.7-3.1 kg]	1.9 kg [1.45-2.65 kg]	For both pig slurry and dairy cow slurry a reduction of 32% [7-49%] compared to reference scenario have been used (Dansk Landbrugsrådgivning, 2004c). Pig slurry: 3.29 kg*(1-0.32)= 2.2 kg Dairy cow slurry: 2.85 kg*(1-0.32) = 1.9 kg
Ammonia (NH ₃ -N)	0.318 kg	0.275 kg	Pig slurry: 70% reduction compared to reference scenario. 1.06 kg*(1-0.70) = 0.318 kg Dairy cow slurry: 50% reduction compared to reference scenario. 0.55 kg*0.5 = 0.275 kg.
Direct emissions of Nitrous oxide (N ₂ O-N)	0.0022 kg [0.00013 - 0.0055 kg]	0.0024 kg [0.00014- 0.0059 kg]	For both pig slurry and dairy cow slurry a reduction of 83% [58-99%] compared to reference scenario have been used (Dansk Landbrugsrådgivning, 2004c). Pig slurry: 0.013 kg*(1-0.83)= 0.0022 kg Dairy cow slurry: 0.014 kg*(1-0.83) = 0.0024 kg
Nitrogen monoxide (NO-N)	0.0022 kg	0.0024 kg	Estimate based on Dämmgen and Hutchings (2008), see Annex A.
Nitrogen dioxide (NO ₂ -N)	-	-	Assumed to be covered by NO _x emissions, represented as NO emissions above, see text.
Nitrogen (N ₂ -N)	0.0066 kg	0.0072 kg	Estimate based on Dämmgen and Hutchings (2008), see Annex A.
Indirect emissions of Nitrous oxide (N ₂ O-N)	0.0037 kg	0.0028 kg	The indirect emissions of nitrous oxide are caused by NH ₃ and NO _x emissions. This corresponds to 0.01 kg N ₂ O-N per kg (NH ₃ -N + NO _x -N) volatilised (IPCC, 2006, table 11.3). As the NH ₃ and NO _x emissions are reduced, the indirect N ₂ O emissions are also reduced.
Discharges to water			
	None	None	Assumed to be none, as leakages from housing systems are prohibited in Denmark.
Discharges to soil			
	None	None	Assumed to be none, as leakages from housing systems are prohibited in Denmark.

As described in Annex A, it is assumed that the NO emissions cover the total NO_x emissions (NO_x = NO + NO₂) when taking the uncertainty on the rough estimate into account. Hence, additional NO₂ emissions are not added.

As for the reference scenario, the indirect N₂O emissions have been included in accordance with the IPCC (2006) recommendations, the see Appendix A. The indirect N₂O emission corresponds to 0.01 kg N₂O-N per kg (NH₃-N + NO_x-N volatilised) (IPCC, 2006, table 11.3).

The reduction of hydrogen sulphide emissions is discussed by Ottosen et al. (2009), as mentioned above. However, it has not been possible to quantify the reduction.

The mass balances in table B.2 and B.3 are established in order to calculate the composition of the slurry ex acidification plant.

Table B.2.
Calculation of the composition of acidified slurry after the acidification plant (scenario F) for pig slurry.

	Ex animal (A)	Mass balances and calculations		Ex Acidification plant (D) = (C) * 1000 kg/ 1000 kg ^a
		Change during in-house storage (B) (based on references)	Ex acidification plant total (C) = (A)+(B)	
Total mass	1000 kg Slurry ex animal	Assumption: no change ^a	1000 kg	1000 kg Slurry ex acidification
Dry matter (DM)	77.4 kg	- 3.98 kg ^f	73.4 kg	73.4 kg
Ash content	13.2 kg	Assumption: No change	13.2 kg	13.2 kg
Volatile solids (VS)	64.2 kg	- 3.98 kg ^e	60.2 kg	60.2 kg
Total-N	6.60 kg	-0.329 kg N ^b	6.27 kg	6.27 kg
NH ₄ -N	No data	No data	No data	No data
Total-P	1.13 kg	No change	1.13 kg	1.13 kg
Potassium (K)	2.85 kg	No change	2.85 kg	2.85 kg
Carbon (C)	37.0 kg	-2.3 kg ^c	34.7 kg	34.7 kg
Sulphur (S)	No data	+ 1.6 kg	+ 1.6 kg	+ 1.6 kg
Copper (Cu)	30.0 g	No change	30.0 g	30.0 g
Zinc (Zn)	89.4 g	No change	89.4 g	89.4 g
Density	1053 kg per m ³	No change		1053 kg per m ³
pH	7.8	Acidification	5.5	5.5

^a The total amount of slurry is only changed slightly – 5 kg of sulphuric acid is added, and 4.9 kg is lost as emissions. For the calculations, it is assumed that the total mass is not changed (as in the reference scenario).. The assumption has only very little significance for the concentrations.

^b Changes in total N: 0.318 kg NH₃-N + 0.0022 kg N₂O-N + 0.0022 kg NO-N + 0.0066 kg N₂-N = 0.329 kg N

^c Changes in total C: 2.34 kg CO₂ * 12.011 [g/mol] /44.01 [g/mol] + 2.2 kg CH₄ * 12.011 [g/mol] /16.04 [g/mol] = 2.3 kg C

^d Changes in total S: 5 kg H₂SO₄ * 32.054 [g/mol] / 98.077 [g/mol] = 1.63 kg S

^e It is assumed that the change in VS is proportional with the loss of C i.e. 2.3 kg / 37 kg = 6.2%.
64.2 kg * 6.2% = 3.98 kg.

^f It is assumed that the change in DM is identical to the VS loss and that there is no change in the Ash content.

Table B.3.

Calculation of the composition of acidified slurry after the acidification plant (scenario F) for dairy cow slurry.

	Ex animal (A)	Mass balances and calculations		Ex Acidification plant (D) = (C) * 1000 kg/ 1000 kg ^a
		Change during in-house storage (B) (based on references)	Ex acidification plant total (C) = (A)+(B)	
Total mass	1000 kg Slurry ex animal	Assumption: no change ^a	1000 kg	1000 kg Slurry ex acidification
Dry matter (DM)	125.7 kg	- 6.6 kg ^f	119.1 kg	119.1 kg
Ash content	21.5 kg	Assumption: No change	21.5 kg	21.5 kg
Volatile solids (VS)	104.2 kg	- 6.6 kg ^e	97.6 kg	97.6 kg
Total-N	6.87 kg	-0.287 kg N ^b	6.58 kg	6.58 kg
NH ₄ -N	No data	No data	No data	No data
Total-P	1.02 kg	No change	1.02 kg	1.02 kg
Potassium (K)	5.81 kg	No change	5.81 kg	5.81 kg
Carbon (C)	55.2 kg	-3.5 kg ^c	51.7 kg	51.7 kg
Sulphur (S)	No data	+ 1.96 kg	+ 1.96 kg	+ 1.96 kg
Copper (Cu)	12.1 kg	No change	12.1 kg	12.1 kg
Zinc (Zn)	23.4 kg	No change	23.4 kg	23.4 kg
Density	1053 kg per m ³	No change		1053 kg per m ³
pH	7.8	Acidification	5.5	5.5

^a The total amount of slurry is only changed slightly – 7 kg of sulphuric acid is added, and 9.9 kg is lost as emissions. For the calculations, it is assumed that the total mass is not changed (as in the reference scenario). The assumption has only very little significance for the concentrations.

^b Changes in total N: 0.275 kg NH₃-N + 0.0024 kg N₂O-N + 0.0024 kg NO-N + 0.0072 kg N₂-N = 0.287 kg N

^c Changes in total C: 7.7 kg CO₂ * 12.011 [g/mol] / 44.01 [g/mol] + 1.9 kg CH₄ * 12.011 [g/mol] / 16.04 [g/mol] = 3.5 kg C

^d Changes in total S: 6 kg H₂SO₄ * 32.054 [g/mol] / 98.077 [g/mol] = 1.96 kg S

^e It is assumed that the change in VS is proportional with the loss of C i.e. 3.5 kg / 55.2 kg = 6.3%.

104.2 kg * 6.3% = 6.6 kg.

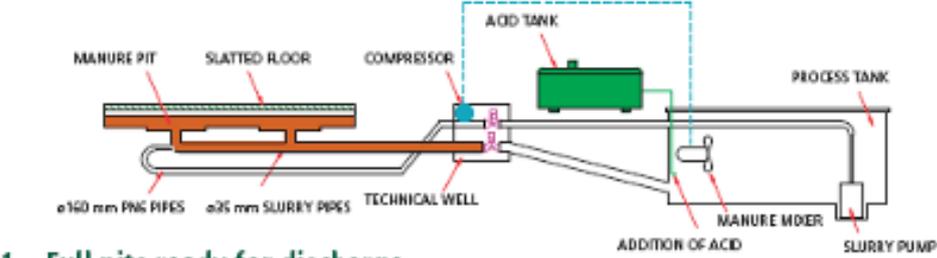
^f It is assumed that the change in DM is identical to the VS loss and that there is no change in the Ash content.

B.3 Acidification of slurry in Infarm NH₄⁺ system

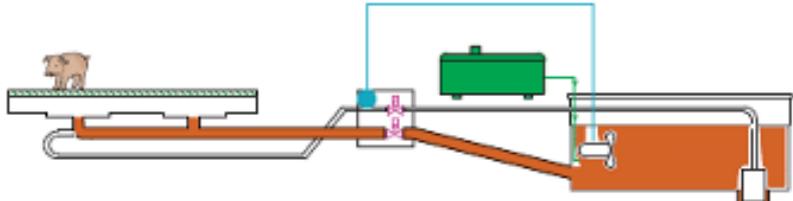
The concept of the slurry acidification technology is to lower pH value of the slurry to 5.5 via the utilisation of sulphuric acid (H₂SO₄). The working principles on how this is done is visualised in figure B.2 and figure B.3 below.

Figure B.2 depicts an acidification installation for pig slurry, where the slurry is discharged, treated and the majority is returned to the stables. The remaining pig slurry is pumped to the outdoor slurry storage. This process is carried out approximately one time per day to ensure that the pH remain at the desired low level.

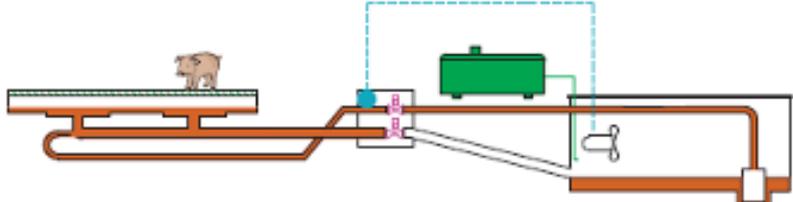
Figure B.2: An Acidification installation for pig slurry, where the pig slurry is discharged, treated and the majority is returned to the stables.



1. Full pits ready for discharge.



2. Manure is led to process tank. The manure is aerated and pH-adjusted with concentrated sulphuric acid.



3. A portion of the treated manure is pumped back to the manure pits, while the remainder is pumped to storage.

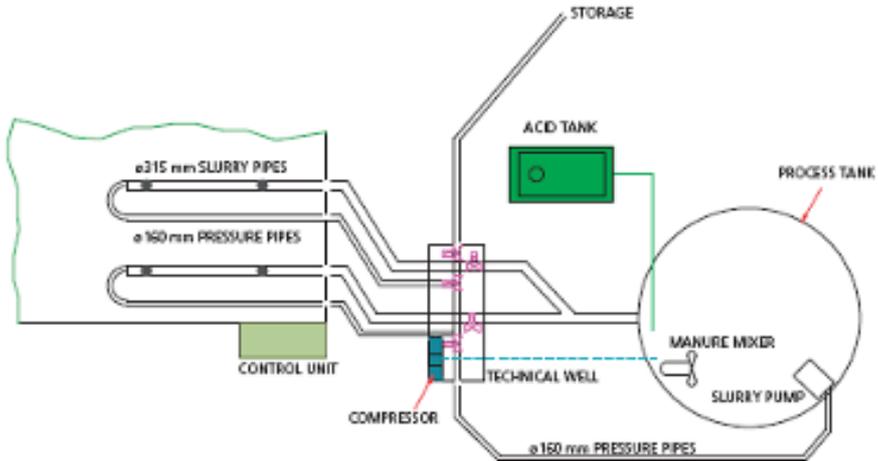
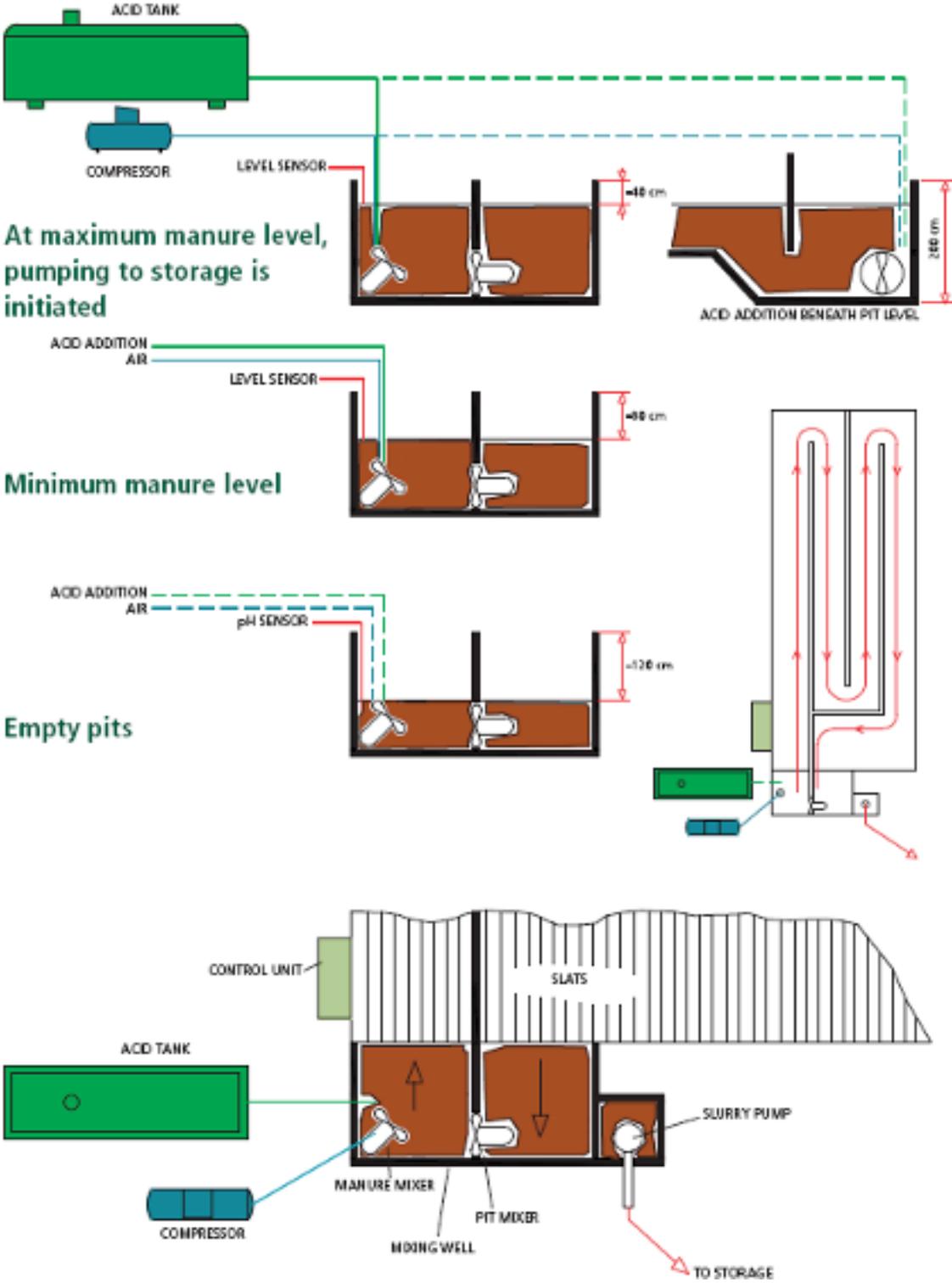


Figure B.3 illustrates an acidification installation for dairy cow slurry, where the acid is added in the mixing well just outside the housing. The mixing well is an integral part of the slurry pits, so the acidification is carried on the entire volume of slurry.

Figure B.3: An Acidification installation for cattle slurry.



The life cycle data for the acidification plant includes extra electricity for pumps and consumption of sulphuric acid. The emissions are included under the data for the in-house storage of acidified slurry in section B.2.

The electricity consumption is based on measurements by Infarm and upcoming BAT-documentation, which have been sent for public hearing until 15 April 2009 (revised version of 23 March 2009 for pig slurry and revised version of 17 March 2009) (BAT (2009a) and BAT (2009b)). In the time of writing these have not been finally approved, however, these are used as basis for the calculations in this study, as they are regarded as the most updated knowledge about the acidification installations.

As can be seen in table B.2, the energy consumption for an acidification plant for pig slurry is significant higher than for an acidification plant for cattle slurry. This is due to differences in the construction of the slurry pits below the animals. For cattle, the slurry from the slurry pits is mixed with the sulphuric acid in a relatively small pre-tank and recycled back into to slurry pits in a iterative process (the process mainly needs energy to run a mixer for recycling the slurry). The construction for pig slurry is more complicated. The slurry in the slurry pits are emptied in a batch process to a process tank, where it is stirred and mixed with the sulphuric acid before it is recycled into the slurry pits. Energy is needed for stirring and pumping amounts of slurry.

For the acidification of pig slurry, 5 kg [4-6kg] concentrated sulphuric acid is used (BAT 2009a). For the acidification of dairy cow slurry, 6 kg [5-7 kg] concentrated sulphuric acid is used (BAT 2009b).

For the production of sulphuric acid, see next section (B.4 “Production of Sulphuric Acid (H₂SO₄)”

Inventory data for the acidification of slurry are shown in table B.4.

Table B.4.
Life cycle Inventory data for acidification of slurry (scenario B).
All data per 1000 kg of slurry "ex animal".

	Fattening pig slurry	Dairy cow slurry	Comments
Input			
Slurry "ex animal"	1000 kg	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 acidification plant"	1000 kg	1000 kg	Mass balances, see table B.4.
Energy consumption			
	3kWh	1 kWh	Pig slurry: BAT (2009a) Cattle slurry: Infarm (J R Lorenzen, 2009)
Consumption of chemicals, materials etc.			
Sulphuric acid	5 kg [4-6 kg]	6 kg [5-7 kg]	BAT (2009a) and BAT (2009b)
Emissions to air			
			Emissions are included under the data for the in-house storage of acidified slurry in section B.2.
Discharges to water			
	None	None	Assumed to be none, as leakages from housing systems are prohibited in Denmark.
Discharges to soil			
	None	None	Assumed to be none, as leakages from housing systems are prohibited in Denmark.

The materials for the acidification plant are shown in table B.5. The materials for the storage tank are at the same level as the materials for the pre-tank under the housing units in the reference scenario and will be included as this.

Table B.5.
Material consumption for an acidification 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]
Acidification Plant					
Steel in tank	2 000 kg	15 years	10000 m ³ / y	150000 m ³	13.3 g
Steel in pump	50 kg	15 years	10000 m ³ / y	150000 m ³	0.3 g
Concrete (plant for <i>pig slurry only</i>)	130 000 kg	15 years	10000 m ³ / y	150000 m ³	867 g
Copper in pump	20 kg	15 years	10000 m ³ / y	150000 m ³	0.13 g
Copper in cables	10 kg	15 years	10000 m ³ / y	150000 m ³	0.066 g
Electronics	2 kg Modelled as 1 laptop	5 years	10000 m ³ / y	50000 m ³	2 E-5 laptop

The density of slurry roughly 1000 kg per m³ used for these estimates (as it is rough estimates anyway).

B.4 Production of sulphuric Acid (H₂SO₄)

The production of the sulphuric acid for the acidification of slurry is included in the life cycle assessment. As this life cycle is based on the consequential approach (see the method description in section 2.3) the “marginal production” of sulphuric acid should be used for the modeling. It means that the production method, that is *affected* when increasing the consumption of sulphuric acid should be identified – not just “the average” production.

In Denmark, sulphuric acid is produced as a by-product from the flue gas cleaning from the electricity production. However, this production of sulphuric acid is not considered to be the “marginal production”. According to Dansk Elforsyning (2006), the production of sulphuric acid as a by-product of electricity production was 5000 tons in 2006, which is a rather limited amount ². Furthermore, it could be mentioned, that if the sulphuric acid from the Danish flue gas cleaning is not bought for acidification of slurry, it would be bought by someone else and thereby replacing another production of sulphuric acid.

In this study, the production of sulphuric acid is included by the use of the Ecoinvent process “ Sulphuric acid, liquid, at plant/RER U”. However, this process is modified slightly in order to transfer the process from “average production” to “marginal production” ³.

² In rough numbers, there is used 5 kg sulphuric acid per 1000 kg pig slurry, which approximately corresponds to the slurry amount from 2 fattening pigs in their life time. Accordingly, the production of 5000 tons of sulphuric acid could at maximum acidify the slurry from 2 000 000 fattening pigs. This is of course not the case as the sulphuric acid is sold for other purposes as well and as there is not acidification plants in Denmark at farms corresponding to 2 000 000 pigs but it shows that the amount of sulphuric acid from the Danish electricity production is limited.

³ According to the background documentation reports for the Ecoinvent database (Nemecek and Kägi, 2007), the sulphur resource for the process is mainly based on liquid sulphur obtained from desulphurization of natural gas or crude oil and cleaning of coal flue gas. In the Ecoinvent database, part of the extraction of the crude oil and natural gas is allocated to the liquid sulphur, which is not in accordance with the consequential approach: The desulphurization of natural gas and crude oil is performed to avoid damages in the refinery installations rather than with the aim of producing sulphuric acid. The liquid sulphur is a by-product which is utilized for production of sulphuric acid, not a main product. Accordingly, in this study, the contribution from the extraction of oil and gas has been deleted. Remaining is the energy and emissions from the transformation of the liquid sulphur into sulphuric acid.

Furthermore, the process is adjusted by a factor 1/0.65. under the documentation for this process, it is stated that: ***“Since the sulphuric acid can be considered a as byproduct from the processing of sulphide ores (other than pyrites), for this study it is considered that the sulphuric acid produced by smelter gas burning is obtained “gratis”. As mentioned above, this process contributes with 35% to the total production. Consequently, in order to subtract the contribution of this process to the overall average, all the values for inputs and outputs presented in the report have been balanced by multiplying them by 0.65.”*** This Ecoinvent approach is not in accordance with the consequential approach, the Ecoinvent process has been adjusted by a factor of 1/0.65 = 1.538.

B.5 storage of acidified slurry

In the reference scenario, the process “Storage” includes storage of slurry in the pre-tank and outdoor storage of slurry. As described in Annex A, it has not been possible to separate the pre-tank emissions from the emissions caused by the outdoor storage.

The same problem occurs in this scenario for acidification: It would have been optimal if the emissions from the acidification process tank could have been separated from the emissions from the outdoor storage. However, it is not possible. Accordingly, this process called “Storage of acidified slurry” includes emissions from:

- Storing slurry in the process tank of the acidification plant
- Storing slurry in the outdoor storage for months before application to fields

Furthermore, the energy consumption is included for stirring and pumping (other than required for the acidification of slurry).

No additional chemicals or additives are added. During the storage, rain is adding water to the slurry. Accordingly, the total amount of slurry is slightly higher after storing, as described in the mass balances chapter 3. There are no wastes or by-products from the process.

The Life Cycle Inventory data for outdoor storage of slurry is given in table B.7. The inputs to the processes are 1000 kg of slurry “ex acidification plant”. All emissions and consumptions are calculated relative to this 1000 kg of slurry going into the process.

The CH₄ emission during outdoor storage of acidified slurry is based on a very rough estimate, as practical scale measurements are not available. There is likely to be a significant reduction of CH₄ emissions when acid is added to slurry. Laboratory-scale storage of cattle slurry for 3 months showed a reduction of 90% of CH₄ emissions. Another study based on in-door storage (Hansen et al., 2008) showed a reduction of the CH₄ emissions by 67% for storage of acidified cattle slurry compared to untreated slurry. However, these indoor test results cannot be directly transferred to long-term outdoor storage of slurry and field tests are needed (personal communication with S.O. Petersen, 2009). It is difficult to assess if the relative reduction will be as high for outdoor storage, as the measurements at room temperature, as the outdoor storage during winter will be significantly lower as the emissions will be reduced by the lower temperature also for untreated slurry. Furthermore, the storage time is much longer for “real life outdoor storage” which will also affect the relative reductions. Since it has not been possible to find field data on the CH₄ emissions from acidified pig slurry, in this study the calculations will assume a reduction of 60% of the CH₄ emission (as a conservative estimate). Sensitivity analysis is carried out for reductions of 30% and 90%. No data has been found on pig slurry. The same assumptions have been made for pig slurry, i.e. a reduction of 60% and sensitivity analysis for 30% and 90%.

No data have been found for the carbon dioxide emissions. As methane is a much stronger greenhouse gas than carbon dioxide, the carbon dioxide emissions are relatively unimportant for the total contributions from the

housing units. It has been assumed that the carbon dioxide emissions are reduced by the same factor as the methane emissions.

The ammonia emissions are reduced by 90% compared to untreated pig slurry (Kai et al., 2007). According to the upcoming BAT notes (BATbyggeblad . (BAT, 2009a and Dansk Landbrugsrådgivning (2004a) (BAT byggeblad 107.04-52) the ammonia emissions during storage are reduced by 50% for both cattle slurry and pig slurry. In this study, a reduction of 50% has been applied.

Nitrous oxide (N_2O) emissions were reduced by 37% in a study made by Hansen (2008). However, Hansen (2008) states that the N_2O reductions might be explained by a lower dry matter content of the acidified slurry and the by the much thicker natural crust formed on top of the untreated slurry. Accordingly, the data is regarded as “up to 37% reduction” in this study. A sensitivity analysis is carried out for the reduction.

The emissions of NO , NO_2 and N_2 are calculated using the same assumptions as for the in-house storage in section B.2. For the indirect N_2O emissions, see text in table B.7 and in section B.2.

The energy consumption for pumping and stirring that are *not* particularly related to the acidification of slurry is assumed to be identical to the energy consumption in the reference scenario in Annex A. This includes:

- Stirring slurry in the pre-tank before pumping to the outdoor storage.
- Pumping slurry from the pre-tank to the outdoor storage by a pump.
- Stirring slurry in the outdoor concrete tank when straw is added (pig slurry only)
- Stirring slurry before pumping from outdoor storage tank.
- Pumping slurry from the storage tank to the transport tank.

The energy consumption for these processes are assumed to be on the same level in the reference scenario and for the system for acidification of slurry in this Annex (see Annex A for details). In addition to this energy consumption the energy consumption for the acidification plant has been added, see table B.4.

It is assumed, that there are no emissions to water and soil from slurry storage as in the reference scenario.

Table B.6

Life cycle data for outdoor storage of acidified slurry. All data per 1000 kg of slurry "ex acidification plant".

	Fattening pig slurry	Dairy cow slurry	Comments
Input			
Slurry "ex housing"	1000 kg	1000 kg	The reference slurry for the process "outdoor storage of slurry" is slurry "ex housing" i.e. the emissions are calculated relative to this.
Cut straw	2.5 kg	None	Cut straw is added for floating layer during storage for pig slurry. It is assumed that it is not necessary to add cut straw to the cattle slurry (Rasmussen et al., 2001, page 31).
Concrete slurry store	Included	Included	Estimate included based on data from the Ecoinvent process: "Slurry store and processing, operation", see text above.
Output			
Slurry "ex storage"	1086 kg	1044 kg	Same assumptions as in Annex A.
Energy consumption			
Electricity	4.6 kWh	3.4 kWh	As in Annex A
Emissions to air			
Carbon dioxide (CO ₂)	0.072 kg	1.68 kg	No data has been available. It is assumed that the CO ₂ emissions are reduced by the same factor as the CH ₄ emissions. Pig slurry: 0.18 kg * (1-0.60) = 0.072 kg Cattle slurry: 4.21 kg * (1-0.60) = 1.68 kg
Methane (CH ₄)	0.78 kg	0.67 kg	CH ₄ emissions reduced by 60% compared to the reference scenario (see text above). Pig slurry: 1.94 kg * (1-0.60) = 0.78 kg Cattle slurry: 1.68 kg * (1-0.60) = 0.67 kg
Ammonia (NH ₃ -N)	0.055 kg	0.065 kg	NH ₃ emissions reduced by 50% compared to the reference scenarios (Kai et al., 2007). Pig slurry: 0.11 kg * 0.5 = 0.055 kg Cattle slurry: 0.13 kg * 0.5 = 0.065 kg
Direct emissions of Nitrous oxide (N ₂ O-N)	0.021 kg	0.021 kg	Up to 37% reduction (Hansen, 2008). Pig slurry: 0.033 kg * (1-0.37) = 0.21 kg Cattle slurry: 0.034 kg * (1-0.37) = 0.21 kg
Nitrogen monoxide (NO-N) (representing total NO _x)	0.021 kg	0.021 kg	Estimate based on Dämmgen and Hutchings (2008), see Annex A.
Nitrogen (N ₂ -N)	0.063 kg	0.063 kg	Estimate based on Dämmgen and Hutchings (2008), see Annex A.
Indirect emissions of Nitrous oxide (N ₂ O-N)	0.00076 kg	0.00086 kg	The indirect emissions of nitrous oxide are caused by NH ₃ and NO _x emissions. This corresponds to 0.01 kg N ₂ O-N per kg (NH ₃ -N + NO _x -N) volatilised (IPCC, 2006, table 11.3). As the NH ₃ and NO _x emissions are reduced, the indirect N ₂ O emissions are also reduced.
Discharges to water			
	None	None	Assumed to be none, as leakages from slurry tanks are prohibited in Denmark
Discharges to soil			
	None	None	Assumed to be none, as leakages from slurry tanks are prohibited in Denmark

The mass balances in table B.7 and B.8 are established in order to calculate the composition of the slurry storage. According to Sørensen and Eriksen (2009), the $\text{NH}_4^+\text{-N}/\text{Total N}$ ratio for acidified slurry is 0.82 for pig slurry and 0.59 for cattle slurry ex storage. The composition ex acidification plant is taken from table. B.2 and B.3.

Table B.7.

Calculation of the composition of acidified slurry after outdoor storage for pig slurry.

	Ex Acidification plant (A)	Mass balances and calculations		Ex storage (D) = (C) * 1000 kg/ 1086 kg ^a
		Change during storage (B) (based on references)	Ex storage total (C) = (A)+(B)	
Total mass	1000 kg slurry ex acidification	+86 kg ^a	1086 kg	1000 kg slurry ex storage
Dry matter (DM)	73.4 kg	- 1.0 kg ^f	73.4 kg	67.6 kg
Ash content	13.2 kg	Assumption: No change	13.2 kg	12.2 kg
Volatile solids (VS)	60.2 kg	- 0.5 kg ^e	59.7 kg	55.0 kg
Total-N	6.27 kg	-0.16 kg N ^b	6.11 kg	5.63 kg
$\text{NH}_4\text{-N}$	No data	No data	No data	4.62 kg ^d
Total-P	1.13 kg	No change	1.13 kg	1.04 kg
Potassium (K)	2.85 kg	No change	2.85 kg	2.62 kg
Carbon (C)	34.7 kg	-0.6 kg ^c	34.1 kg	31.4 kg
Sulphur (S)	+ 1.6 kg	No change	+ 1.6 kg	+ 1.5 kg
Copper (Cu)	30.0 g	No change	30.0 g	27.6 g
Zinc (Zn)	89.4 g	No change	89.4 g	82.4 g
Density	1053 kg per m ³	-	1053 kg per m ³	1053 kg per m ³
pH	5.5	Slight increase	5.7	5.7

^a For the outdoor storage, the same dilution factor is used for acidified slurry as in the reference scenario, i.e.+8.6%, see table A.4 in Annex A.

^b Changes in total N: $0.055 \text{ kg NH}_3\text{-N} + 0.021 \text{ kg N}_2\text{O-N} + 0.021 \text{ kg NO-N} + 0.0066 \text{ kg N}_2\text{-N} = 0.16 \text{ kg N}$

^c Changes in total C: $0.072 \text{ kg CO}_2 * 12.011 [\text{g/mol}] / 44.01 [\text{g/mol}] + 0.78 \text{ kg CH}_4 * 12.011 [\text{g/mol}] / 16.04 [\text{g/mol}] = 0.6 \text{ kg C}$

^d According to Sørensen et al. (2009), the $\text{NH}_4\text{-N}/\text{Total N}$ ratio for acidified slurry is 0.82 for pig slurry and 0.59 for cattle slurry.

^e It is assumed that the change in VS is proportional with the loss of C i.e. $0.6 \text{ kg} / 34.7 \text{ kg} = 1.7\%$.
 $60.2 \text{ kg} * 1.7\% = 1.0 \text{ kg}$.

^f It is assumed that the change in DM is identical to the VS loss and that there is no change in the Ash content.

Table B.8.

Calculation of the composition of acidified slurry after outdoor storage for dairy cow slurry.

	Ex Acidification plant	Mass balances and calculations		Ex storage
	(A)	Change during storage (B) (based on references)	Ex storage total (C) = (A)+(B)	(D) = (C) * 1000 kg/ 1044 kg ^a
Total mass	1000 kg slurry ex acidification	+ 44 kg ^a	1044 kg	1000 kg slurry Ex storage
Dry matter (DM)	119.1 kg	- 0.5 kg ^f	118.6 kg	113.6 kg
Ash content	21.5 kg	Assumption: No change	21.5 kg	20.6 kg
Volatile solids (VS)	97.6 kg	- 1.8 kg ^e	95.8 kg	91.8 kg
Total-N	6.58 kg	-0.17 kg N ^b	6.41 kg	6.14 kg
NH ₄ -N	No data	No data	No data	3.62 kg ^d
Total-P	1.02 kg	No change	1.02 kg	0.98 kg
Potassium (K)	5.81 kg	No change	5.81 kg	5.57 kg
Carbon (C)	51.7 kg	- 0.96kg ^c	50.7 kg	48.6 kg
Sulphur (S)	+ 1.96 kg	No change	+ 1.96 kg	1.88 kg
Copper (Cu)	12.1 kg	No change	12.1 kg	11.6 g
Zinc (Zn)	23.4 kg	No change	23.4 kg	22.4 g
Density	1053 kg per m ³	No change	1053 kg per m ³	1053 kg per m ³
pH	5.5	Slight increase	5.7	5.7

^a For the outdoor storage, the same dilution factor is used for acidified slurry as in the reference scenario, i.e. +4.4%, see table A.4 in Annex A.

^b Changes in total N: 0.065 kg NH₃-N + 0.021 kg N₂O-N + 0.021 kg NO-N + 0.063 kg N₂-N = 0.17 kg N

^c Changes in total C: 1.68 kg CO₂ * 12.011 [g/mol] /44.01 [g/mol] + 0.67 kg CH₄ * 12.011 [g/mol] /16.04 [g/mol] =0.96 kg C

^d According to Sørensen et al. (2009), the NH₄⁺-N/Total N ratio for acidified slurry is 0.82 for pig slurry and 0.59 for cattle slurry.

^e It is assumed that the change in VS is proportional with the loss of C i.e. 0.96kg / 51.7 kg = 1.86%.
97.6 kg * 1.86% = 1.8 kg.

^f It is assumed that the change in DM is identical to the VS loss and that there is no change in the Ash content.

B.6 Transport of acidified slurry to field

The transport of acidified slurry to field is assumed to be identical to the transport of untreated slurry in the reference scenario, see Annex A.

B.7 Field processes (acidified slurry)

The process “Field processes (acidified slurry)” includes the same processes as for untreated slurry in the reference scenario. The application of slurry by trail hose application tanker and the diesel consumption is assumed to be identical.

However, acidification of slurry changes some of the emissions and as the content of N in the slurry is higher in acidified slurry (due to reduced loss of NH₃ in the housing units and during storage) than for untreated slurry. This leads to that the fertilizer value of acidified slurry is higher than the fertilizer

value of untreated slurry (Sørensen and Eriksen, 2009), Sørensen (2006) and Jensen (2006).

The CO₂ emissions are modeled by C-tool by B M Petersen (2009).

The CH₄ emission on the field is assumed to be negligible, as the formation of CH₄ requires anaerobic environment, and at the field is normally plenty of oxygen.

The NH₃ emissions during the very application are assumed to correspond to 33% of the NH₃ emissions from untreated slurry (Kai et al. (2008) and Hansen et al. (2008)). As the NH₃ emissions during the very application are assumed to correspond 0.5% of the NH₄⁺ content of the slurry for the untreated slurry, the NH₃ emissions during the very application of acidified slurry are assumed to correspond $0.5\% \cdot 0.33 = 0.165\%$.

Hansen et al. (2008) estimate that the NH₃ emissions from acidified slurry applied to field are is approximately 33% of the NH₃ emissions from untreated slurry.

The direct N₂O emissions from acidified slurry are calculated by the same method as for the untreated slurry, i.e. as 0.01 kg N₂O-N per kg N “ex storage” for application of animal wastes to soil, based on IPCC (2006, table 11.1), see Annex A. As the total N content of the acidified slurry is slightly higher than the total N in the untreated slurry, the N₂O emission will be slightly higher as well. It should be emphasised that this assumption (that the N₂O emissions from application of acidified slurry to field is at the same level as untreated slurry) is a rather rough assumption without any reference to measurements or testing. The composition of the slurry is rather different than untreated slurry and it might affect the N₂O emissions from the field. The area needs scientific research.

In addition, the indirect N₂O emission has been included in accordance with the IPCC (2006) guidelines, as described in section A.2, i.e. 0.01 kg N₂O-N per kg (NH₃-N + NO_x-N volatilised) (IPCC, 2006, table 11.3).

The emissions of nitrogen oxides (NO_x) and nitrogen (N₂) is based on the same assumptions as in Annex A, see this.

According to Petersen and Sørensen (2008), application of acidified slurry to fields leads to an increased need for application of lime, corresponding to 300-600 kg CaCO₃/ha per year. With 30 tons slurry per ha it corresponds to an increase of the lime consumption of 15 kg CaCO₃ per 1000 kg slurry. The Ecoinvent process “Limestone, milled, loose, at plant/CH U” has been used for the modeling. The marginal lime production has not been identified within the frames of the project, as it is insignificant for the overall results. According to Dalgaard (2002), the amount of diesel used for applying lime to fields is 1.5 liter diesel per ha per year (corresponding to 0.05 liter diesel per 1000 kg slurry). The energy consumption for applying lime is included by the use of the Ecoinvent process “Application of plant protection products, by field sprayer/CH U” as a proxy.

The added lime is assumed to lead to a CO₂ emission corresponding to the total amount of added carbonate according to IPCC (2006, section 11.3.1). This is included in table B.9.

In order to obtain values for N leaching, we first calculate the extra N available after ammonia losses, relative to the basis scenario in Annex A. For the pig slurry basis scenario, there is $4.80 - (0.02 + 0.48) = 4.30$ kg N available after ammonia losses (from tables A.5 and A.17). The corresponding figure for the cattle slurry basis scenario is 5.04 kg N available (calculated from tables A.6 and A.17). In the present scenario, there are respectively 5.43 kg N and 5.75 kg N available after ammonia losses, for respectively pig and cattle slurry (calculated from tables B.7, B.8 and B.9). The acidification is assumed to have a minute effect on the amount of organic N in the slurry, so the differences of respectively 1.13 (pig slurry) and 0.71 (cattle slurry) kg N are assumed to be in mineral form. Thereby the fates of the additional N can be considered identical to the mineral N fates of table A.14, after a small correction for the 2% ammonia volatilization assumed in this table. Hereby the **additional** leaching, compared to the basis scenario, for acidified pig slurry can be calculated as follows (JB3, pig slurry): $0.431 * 1.13 \text{ kg N} / (1 - 0.02) = 0.50 \text{ kg N}$. The **total** leaching caused by 1000 kg acidified pig slurry is then $0.50 \text{ kg N} + 1.91$ (from table A.17) = 2.41 kg N. The same principles were applied for all four combinations of soil and slurry types, as seen in table B.9.

As the main difference concerning N, relative to the untreated slurry is an increased amount of mineral N, the nitrate leaching is assumed to rise with the same marginal response as those derived from mineral fertilizer (table A.14). Concerning CO₂, the response only differs by the effect of added production, which causes more storage of C in the soil, and hence less CO₂ emission. This effect is calculated with C-TOOL.

The life cycle inventory data for application of slurry is shown in table B.9.

Table B.9.

Life cycle data for application of slurry and field processes for acidified slurry. All data per 1000 kg of slurry ex outdoor storage.

	Fattening pig slurry	Dairy cow slurry	Comments
Input			
Slurry "ex storage"	1000 kg	1000 kg	Slurry 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	Substitution See section B.8 and B.9	Substitution See section B.8 and B.9	The substitution of is identical to Annex A, but for the addition of substituted S fertiliser.
Energy consumption			
Diesel for application	As in Annex A	As in Annex A	As in Annex A
Consumption of chemicals, materials etc.			
Lime	15 kg CaCO ₃	15 kg CaCO ₃	Modelled by the use of the Ecoinvent process "Limestone, milled, loose, at plant/CH U"
Emissions to air			
Carbon dioxide (CO ₂)			Modelled by C-TOOL (Gyldenkærne et al, 2007). 10 year values, numbers in parenthesis are 100 year values
Soil JB3	77.8 (95.2) kg	122.6 (150.0) kg	
Soil JB6	76.4 (94.7) kg	124.2 (153.9) kg	
Carbon dioxide (CO ₂) caused by liming	1.8 kg	1.8 kg	15 kg CaCO ₃ per 1000 kg slurry * 0.12 CO ₂ per kg (IPCC, section 11.3.1)
Methane (CH ₄)	Negligible	Negligible	The CH ₄ emission on the field is 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	0.008 kg	0.006 kg	NH ₃ emissions during application: 0.165% of toNH ₄ ⁺ content see text above. Pig slurry: 4.69 kg NH ₄ ⁺ * 0.165% = 0.008 kg Cow slurry: 3.65 kg NH ₄ ⁺ * 0.165% = 0.006 kg
Ammonia (NH ₃ -N) after application	0.19 kg	0.38 kg	The NH ₃ emissions from acidified slurry applied to field are approximately 33% of the NH ₃ emissions from untreated slurry. Pig slurry: 0.58 kg * 0.33 = 0.19 kg Cattle slurry: 1.14 kg * 0.33 = 0.38 kg
Direct emissions of Nitrous oxide (N ₂ O-N)	0.057 kg [0.015-0.15]	0.062 kg [0.018-0.18]	0.01 [0.003 - 0.03] kg N ₂ O-N per kg N "ex storage" for application of animal wastes to soil, based on IPCC (2006, table 11.1).
Nitrogen oxides (NO _x -N)	0.0057 kg	0.0062 kg	NO _x -N = 0.1 * N ₂ O-N according to Nemecek and Kägi (2007), see Annex A
Nitrogen (N ₂ -N)	Soil JB3: 0.28 kg Soil JB6: 0.54 kg	Soil JB3: 0.29 kg Soil JB6: 0.58 kg	Estimate from the SimDen model by Vinther (2005), see Annex A.
Indirect emissions of Nitrous oxide (N ₂ O-N)	0.002 kg	0.004 kg	0.01 kg N ₂ O-N per kg (NH ₃ -N + NO _x -N) volatilised (IPCC, 2006, table 11.3). Ammonia emissions given in this table.
Soil JB3	0.018 kg	0.019 kg	Indirect emissions due to nitrate leaching:
Soil JB6	0.014 kg	0.014 kg	0.0075 kg N ₂ O-N pr kg N leaching (IPCC, '06)
Discharges to soil			
Nitrate leaching			See text. 10 year values, numbers in parenthesis are 100 year values
Soil JB3	2.41 (3.04) kg N	2.47 (3.60) kg N	
Soil JB6	1.86 (2.23) kg N	1.90 (2.65) kg N	
Phosphate leaching	0.104 kg P	0.098 kg P	As in Annex A
Copper (Cu)	0.0276 kg	0.0116 kg	As in Annex A
Zinc (Zn)	0.0824 kg	0.0224 kg	As in Annex A

B.8 Avoided mineral fertilisers (N, P and K)

The substitution of fertilizers is estimated as follows. The N content in slurry leads to a substitution of mineral N fertilizer, as described in Annex A. The use of N fertilizer is restricted by Danish law (Gødskningsbekendtgørelsen, 2008, and Gødskningsloven, 2006), and the farmers have to make accounts on their fertiliser use, and they have to include a fixed amount of the N content of the animal slurry in their fertiliser accounts. For acidified slurry, the substitution requirements states that the substitution ratio is set by the producer of the technology, however, the substitution ratio shall be at least the same as for untreated slurry, i.e. 75% for pig slurry and 70% for cattle slurry. As there is no point in setting it higher from a production viewpoint (because the farmers want to be allowed to apply as much N as possible), the substitution ration for acidified slurry is set to 75% for pig slurry and 70% for cattle slurry, as in Annex A. It has the consequence that the relative replacement of N in slurry by mineral N is the **same** as for untreated slurry, however, the acidified slurry has a higher content of N which means that the fields receives a higher amount of plant available N when using acidified slurry, which increases the crop yield as well as the N losses. If the N substitution had been regulated to the real fertilizer value of acidified slurry, the crop yield would presumably not increase.

According to Gødskningsbekendtgørelsen (2008), the substitution value for N is calculated in relation to the Danish Norm data (ex storage values). As the Danish Norm data (ex storage values) do not include losses due to N₂O, NO etc. the N substitution should be calculated in relation to the theoretical content of N in the slurry ex storage from the Norm Data. These are shown in table A.1 and A.2 in Annex A.

It means that the “replaced N fertilizer” is the **same** amount as in Annex A, in spite of that it should have been higher for acidified slurry. This gives an extra amount of N to the field. The assumptions regarding the increased crop yield is discussed in section B.10 below.

For the sensitivity analyses, it has been assumed that the Danish Law is changed, leading to a requirement that the “fertiliser replacement value” reflects the actual content of N in the acidified slurry ex storage.

Calculations of the avoided mineral N fertilisers have been carried out.

- First, the “fertiliser replacement value” for the reference system is stated (see Annex A for further details) for pig slurry: Mineral N fertiliser: 5.00 kg N per 1000 kg slurry ex storage [the value given by the Danish Norm Data, as explained in Annex A] * 1086 kg slurry ex storage per 1000 kg slurry ex animal * 75% [the replacement value according to (Gødskningsbekendtgørelsen, 2008)] = 4.0725 kg mineral N fertiliser
- If the “fertiliser replacement value” for acidified pig slurry where based on measurement, the acidified pig slurry contains 5.63 kg N ex storage (table B.7). 5.63 kg N ex storage * 75% * 1086 kg slurry ex storage per 1000 kg slurry ex animal = 4.586 kg N
- Accordingly, for pig slurry, the farmer should **reduce** the application of mineral N fertiliser by 0.513 kg mineral N fertiliser per 1000 kg slurry ex animal (i.e. corresponding to the functional unit) (as 4.586 kg N - 4.0725 kg = 0.51 kg N). This means that additional of 0.51 kg N fertiliser is avoided per 1000 kg **pig slurry** ex animal.

- Then, the “fertiliser replacement value” for the reference system is stated (see Annex A for further details) for pig slurry: Mineral N fertiliser: 6.02 kg N per 1000 kg slurry ex storage [the value given by the Danish Norm Data, as explained in Annex A] * 1044 kg dairy cow slurry ex storage per 1000 kg slurry ex animal * 70% [the replacement value according to (Gødskningsbekendtgørelsen, 2008)] = 4.399 kg mineral N fertiliser
- If the “fertiliser replacement value” for acidified dairy cow slurry where based on measurement, the acidified dairy cow slurry contains 6.14 kg N ex storage (table B.8). 6.14 kg N ex storage * 70% * 1044 kg slurry ex storage per 1000 kg slurry ex animal = 4.487 kg N
- Accordingly, for pig slurry, the farmer should **reduce** the application of mineral N fertiliser by 0.088 kg mineral N fertiliser per 1000 kg slurry ex animal (i.e. corresponding to the functional unit) (as 4.487 kg N - 4.399 kg = 0.088 kg N). This means that additional of 0.088 kg N fertiliser is avoided per 1000 kg **dairy cow slurry** ex animal.

The amount of P and K is unchanged for the acidified slurry.

B.9 Avoided mineral fertilisers (S)

The sulphur (S) from the sulphuric acid is assumed to replace mineral S fertilizer. It is assumed that the added sulphur in the acidified slurry can replace mineral S fertilizer corresponding to 20 kg S per ha (Birkmose, 2008). With an application of 30 tons slurry per ha it corresponds to 0.67 kg S per 1000 kg slurry. The acidified slurry will add excess amounts of sulphur to the fields, which might result in sulphur leaching (Knudsen, 2008). It has not been possible to include the environmental aspects of sulphur leaching in this life cycle assessment due to that the existing Life Cycle Methods cannot handle sulphur leaching.

No data on the production of mineral S fertiliser has been found. It is basically produced on sulphuric acid, and hence, the avoided production for S mineral fertiliser is assumed to be sulphuric acid.

B.10 Impacts on crop production

According to Sørensen (2006), the increase in fertilizer value for acidified pig slurry corresponds to 39% for winter wheat and 15% for spring barley compared to untreated pig slurry. For acidified cattle slurry, Sørensen (2006) found an increased fertilizer value of 62% for winter wheat and 3% for spring barley compared to untreated cattle slurry. Jensen (2006) found an increased yield of respectively +11.4% (winter wheat in 2001), +6.0% (winter wheat in 2002), -0.2% (decrease) (winter wheat in 2003) and + 9.4% (spring barley in 2003). The fertilizer value is not direct corresponding to the increased yield. In this study, the consequences of adding acidified slurry are modeled as an increased yield of winter wheat of 6.6% (the average of the data above). According to Sørensen (2006), the crop yield was 63.3 t/ha (winter wheat 2001), 61.4 t/ha (winter wheat, 2002) and 59.5 t/ha (winter wheat, 2003) when applying untreated slurry. The average is 61.4 t/ha, and an increase yield of 6.6% then corresponds to 4.05 t/ha. With an

applied amount of 30 tons slurry per ha, the increased yield corresponds to 0.135 hkg per 1000 kg slurry, i.e. 13.5 kg winter wheat per 1000 kg slurry.

In order to estimate the extra crop yield for dairy cow slurry, the extra N available after ammonia losses have been calculated:

- For pig slurry in the reference scenario, the N available after ammonia losses are 4.30 kg N per 1000 kg slurry ex storage ⁴.
- For acidified pig slurry, the N available after ammonia losses are 5.43 kg N per 1000 kg slurry ex storage ⁵.
- This corresponds to a surplus of $5.43 - 4.30 = 1.13$ kg N
- For dairy cow slurry in the reference scenario, the N available after ammonia losses are 5.04 kg N per 1000 kg slurry ex storage ⁶.
- For acidified dairy cow slurry, the N available after ammonia losses are 5.754 kg N per 1000 kg slurry ex storage ⁷.
- This corresponds to a surplus of $5.754 - 5.04 = 0.714$ kg N
- Accordingly, the ratio between pig slurry and dairy cow slurry is $0.714 \text{ kg N} / 1.13 \text{ kg N} = 0.63$

Accordingly, it has been assumed that the increased yield for acidified dairy cow slurry is $13.5 \text{ kg} * 0.63 = 8.5$ kg winter wheat.

When calculating the yield increase with the fitted polynomials described in section A.5, the amount of extra mineral N (as calculated above) is utilized. For pig manure, the extra winter wheat grain yield the crops delivers at the higher fertilization level is 9.7 kg (JB3), respectively 8.8 (JB6). For cattle slurry the values are 6.4 kg, respectively 5.8 kg, because of the lower amount of extra N in acidified cattle slurry, relative to pig slurry.

It is considered to be a fairly uncertain value depending on a lot of factors, and the increased yield should be interpreted with care. The significance is discussed under sensitivity analysis.

It is considered to be a very uncertain value, depending on a lot of factors, and the increased yield should be interpreted with care. The significance is discussed under sensitivity analysis.

The increase of a crop yield of 13.5 kg winter wheat is assumed to replace 13.5 kg winter wheat produced somewhere else in Denmark. This is a very

⁴ $4.80 \text{ kg N per 1000 kg slurry ex storage (table A.1)} - 0.02 \text{ kg NH}_3\text{-N (loss during application, table A.17)} - 0.48 \text{ kg NH}_3\text{-N (loss after application, table A.17)} = 4.30 \text{ kg N per 1000 kg slurry ex storage.}$

⁵ $5.63 \text{ kg N per 1000 kg slurry ex storage (table B.7)} - 0.008 \text{ kg NH}_3\text{-N (loss during application, table B.9)} - 0.19 \text{ kg NH}_3\text{-N (loss after application, table B.9)} = 5.43 \text{ kg N per 1000 kg slurry ex storage.}$

⁶ $5.79 \text{ kg N per 1000 kg slurry ex storage (table A.2)} - 0.02 \text{ kg NH}_3\text{-N (loss during application, table A.17)} - 0.73 \text{ kg NH}_3\text{-N (loss after application, table A.17)} = 5.04 \text{ kg N per 1000 kg slurry ex storage.}$

⁷ $6.14 \text{ kg N per 1000 kg slurry ex storage (table B.8)} - 0.006 \text{ kg NH}_3\text{-N (loss during application, table B.9)} - 0.38 \text{ kg NH}_3\text{-N (loss after application, table B.9)} = 5.754 \text{ kg N per 1000 kg slurry ex storage.}$

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 13.5 kg winter wheat, using data from the process “Wheat, conventional, from farm“ from LCA-food data base (www.lcafood.dk).

Annex C. Samson Bimatech Mechanical Separation – Life Cycle Inventory data

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C.1 System description

This appendix contains Life Cycle Inventory data for the Samson Bimatech mechanical separation plant. The separation plant separates pig or cattle slurry in a fibre fraction and a liquid fraction (“reject”). The fibre fraction is normally regarded as the “primary product” of the separation process.

The fibres are either combusted in the Samson Bimatech Energy Plant (Annex D) or they might be transported to central biogas plants, where the main part of the carbon content is used for biogas production (Annex G of an upcoming report following this).

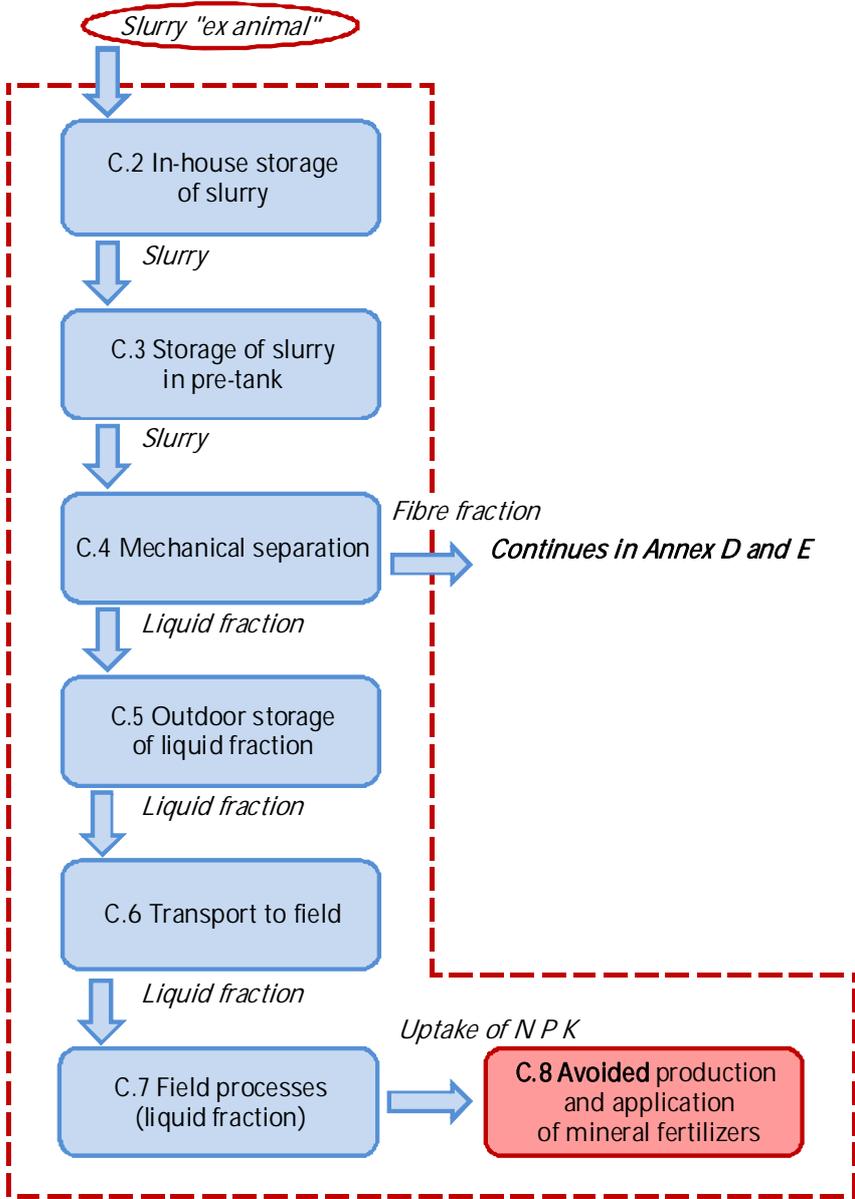
The liquid fraction is pumped to an outdoor storage tank and applied to fields without further treatment.

The Samson Bimatech mechanical separation plant has not yet been tested on cattle slurry. It is scheduled to be April/May 2009. Accordingly, this appendix only includes data on pig slurry.

Stirring and pumping of slurry occurs in and between some of the processes. Stirring and pumping is not shown in the flow diagram in figure C.1 but the energy consumption for stirring and pumping is included in the model as in Annex A.

It should be emphasized that this Annex is not a full “scenario”. The fibre fraction continues in other Annexes (Annex D, Annex E and further biogas-annexes in the upcoming report). A full “scenario” follows the liquid fraction and the fibre fraction to the end – and this annex only covers the liquid fraction.

Figure C.1: Flow diagram for the Samson Bimatech Mechanical Separation.



C.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, see Annex A.

C.3 Storage of slurry in pre-tank

From the housing units, the slurry is flushed (or run by itself) from the slurry space under the column floor to an outdoor pre-tank, typically with top level just below the floor level in the housing units.

In the reference scenario, the emissions from storage of slurry in the indoor slurry space, the pre-tank and emissions from the outdoor storage are

calculated together, as this is the way it is done in the literature references that have been available, see Annex A.

For this scenario, separate emission data from the pre-tank is needed as the slurry is separated, and as it is only part of the slurry that is stored outdoor (i.e. the liquid fraction). However, it has not been possible to identify the relative contribution of the emissions from the pre-tank and the outdoor storage.

Accordingly, the emissions for the storage in the pre-tanks are included under the outdoor storage of liquid fraction of the slurry, adjusted by the relative content of C and N in the liquid fraction of the slurry. This will underestimate the emissions from storage. The assumption is discussed under sensitivity analysis.

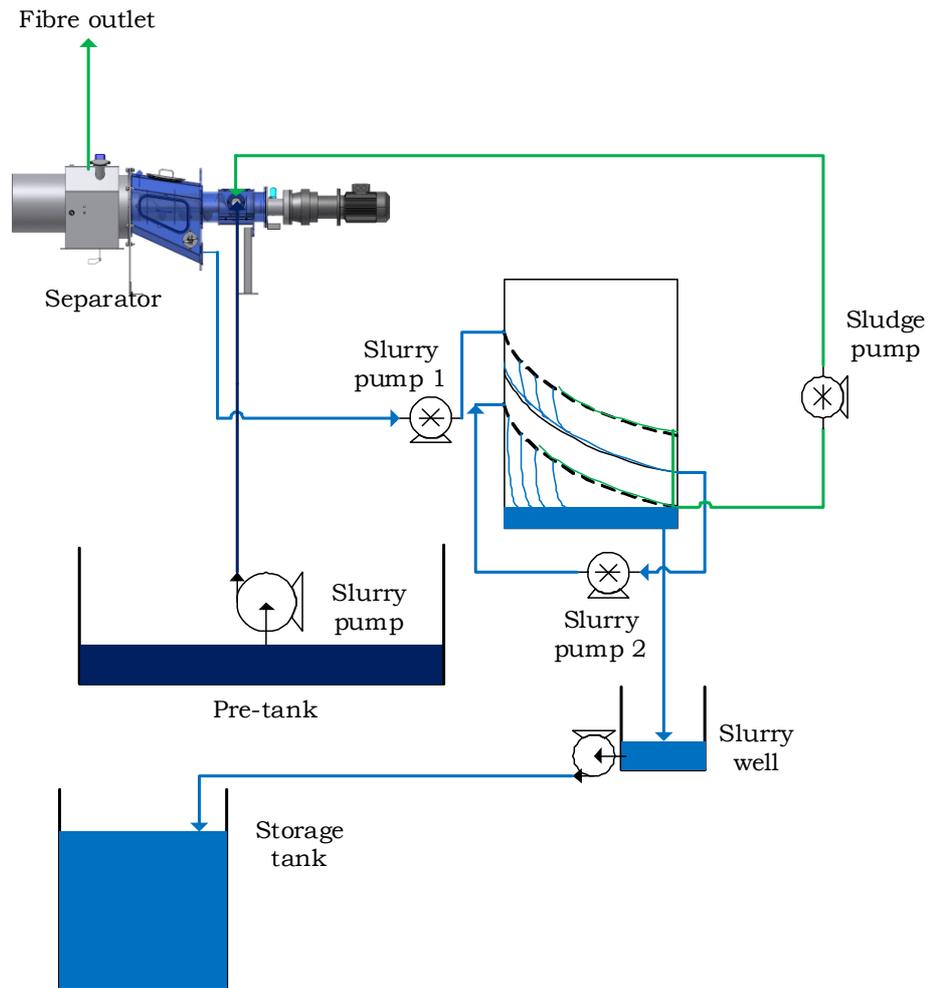
The energy consumption for stirring in the pre-tank and for pumping slurry from the pre-tank is shown in table C.1.

Table C.1
Energy consumption for stirring and pumping slurry during storage in the pre-tank. All data per 1000 kg of slurry "ex housing".

Fattening pig slurry	
Electricity for stirring in the pre-tank before pumping.	1.2 kWh
Electricity for pumping from the pre-tank to the outdoor storage.	0.5 kWh
Total	1.7 kWh

C.4 Samson Bimatech Mechanical Separation

The mechanical separation is done with a screw press machine and an arc strainer in combination. The manure is first led to the separator. The machine consists basically of a screw and a cylindrical filter around. The screw is slowing rotation forward. At the end of the screw is conical opening partly closed (controlled by air pressure) by a cone. The difficulties for the fibres to leave at the end presses the water fraction in tangential direction through a thin layer of fibres and the steel filter with 3 mm round holes. The thin layer of fibres between the screw and the filter acts as an extra filter and makes it possible to filter very small parts and particles from the manure. The wet fraction is led to a box with two arc strainers and passes first one with and later after lifting with a pump the second. The size of the openings of the two are different (in the range 500 – 1000 µm) with the biggest column first in the flow direction. The extra separated particles are pumped back to the separator and is given a new possibility for ending with the dry fraction.



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. The assumption is not strictly correct due to the biological processes in the slurry during the residence time in the stable (a period between one and six weeks) and the pre-tank, however, it has not been possible to identify qualified data on the biological decomposition in the stable and pre-tank.

The efficiency of the mechanical separation is estimated in table C.2

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 to the mass of the compound in the original slurry before separation, i.e.

$$\text{Separation index for N (\%)} = \frac{\text{kg N in solid fraction}}{\text{kg N in slurry before separation}} * 100\%$$

The separation index for N can be interpreted as the percentage of the total N in the raw slurry that ends up in the solid fraction.

The separation index has been calculated for the Samson Bimatech separation plant, and this has been compared to literature data for mechanical screw presses. The separation indexes for mechanical separation using screw presses are shown in table C.2 for pig slurry. It should be noted that none of the mass balances are correct, neither in Møller et al. (2000), Møller et al. (2002) or for the data from Samson Bimatech (i.e the N in the solid fraction + N in the liquid fraction does not correspond with N in the slurry before separation). The deviations in the mass balances are shown in table C.2, and it should be noted that the deviations are rather high, which means that the uncertainty on the measured data is significant.

The separation indexes for DM, N, P and K have been used for calculating the composition of the fiber fraction and the liquid fraction for the separation of the “reference slurry” (from Annex A). However, it has to be emphasized that the separation indexes depend to a high degree on the water content of the water and DM. In “real life”, separation of slurry with a high content of DM will lead to more fibre fraction than separation of slurry with a low content of DM. Accordingly, the use of the separation indexes from table C.2 should be seen as “the best possible approximation” which demands some assumptions, as described below.

First it should be emphasized that the reference pig slurry contains less water than real pig slurry. As described in Annex A, the reference pig slurry 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 slurry¹. If these amounts were included, the DM, N, P and K would be 22% lower. Accordingly, the DM content of the slurry would be 5.7% instead of 6.97%, which is far more realistic when comparing with real pig slurry samples.

¹ 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.

Table C.2.
Separation indexes for mechanical separation of pig slurry.

	Composi- tion of slurry before separation	Fibre fraction/ slurry amount	Composi- tion of fibre fraction	Composi- tion of liquid fraction	Mass balance: Amount in fibre fraction and Separation index [kg] and [%]	Mass balance: Amount in liquid fraction [kg]	Total amount in fibre fraction + liquid fraction and deviation in mass balance [kg]
	[kg/1000 kg slurry]	[%]	[kg/1000 kg slurry]	[kg/1000 kg slurry]			
Total mass							
Ref 1		4.21%			42.1 kg	957.9 kg	
Ref 2a		5.0%			50 kg	950 kg	
Ref 2b		7.3%			73 kg	927 kg	
Samson Bimatech		3.3%			33 kg	967 kg	
Dry matter (DM)							
Ref 1	53.2	4.21%	344.4	42.5	14.5 (27%)	40.7	55.2 (+2)
Ref 2a	56.6	5.0%	317	32	15.9 (28%)	30.4	46.8 (-9.8)
Ref 2b	56.6	7.3%	219	32	16.0 (28%)	29.7	45.7 (-10.9)
Samson Bimatech	44.3	3.3%	396.9	31.1	13.1 (29.6%)	30.1	43.2 (-1.1)
<i>Used in this study</i>					29.6%		
Total-N							
Ref 1	4.20	4.21%	6.61	5.00	0.28 (6.7%)	4.79	5.07 (+0.87)
Ref 2a	4.1	5.0%	4.8	3.0	0.24 (5.9%)	2.85	3.09 (-1.01)
Ref 2b	4.1	7.3%	4.0	4.2	0.29 (7.1%)	3.89	4.18 (+0.08)
Samson Bimatech	4.28	3.3%	8.80	4.04	0.29 (6.8%)	3.91	4.2 (-0.08)
<i>Used in this study</i>					6.8%		
Total-P							
Ref 1	1.26	4.21%	2.13	1.23	0.09 (7%)	1.18	1.27 (+0.01)
Ref 2a	1.4	5.0%	3.3	0.8	0.17 (12%)	0.76	0.93 (-0.47)
Ref 2b	1.4	7.3%	2.9	1.0	0.21 (15%)	0.93	1.14 (-0.26)
Samson Bimatech	0.64	3.3%	1.76	0.57	0.058 (9.1%)	0.55	0.61 (-0.03)
<i>Used in this study</i>					9.1%		
Potassium (K)							
Ref 1	No data	No data	No data	No data	No data	No data	
Ref 2	No data	No data	No data	No data	No data	No data	
Samson Bimatech	1.6	3.3%	1.41	1.64	0.047 (2.9%)	1.586	1.63 (+0.03)
<i>Used in this study</i>					2.9%		
Carbon (C)							
	No data	No data	No data	No data	No data	No data	No data
Copper (Cu)							
	No data	No data	No data	No data		No data	No data
Ref 3					6.4%		
<i>Used in this study</i>					6.4%		
Zinc (Zn)							
	No data	No data	No data	No data		No data	No data
Ref 3					6.3%		
<i>Used in this study</i>					6.3%		

Ref 1: Møller et al. (2002) – pig slurry, screw press separation
 Ref 2a: Møller et al. (2000) – pig slurry, screw press separation, sample no a
 Ref 2b: Møller et al. (2000) – pig slurry, screw press separation, sample no b
 Ref 3: Møller et al. (2007) – data for the screw press separation
 Samson Bimatech: Measurement made on piglet pig slurry 3 February 2009

Due to the lower content of water in the slurry, it has been necessary to adjust the separation index for the total mass of the slurry in order to create a realistic fiber fraction. Accordingly, the liquid fraction from separation of the reference slurry will be “too concentrated” i.e. containing too small amounts of water – like the original reference slurry. It means that one should keep in mind, that the liquid fraction – in real life – probably will contain significantly

more water. The composition of the “theoretically calculated Norm Data fiber fraction” has been compared to measurements of separation of piglet slurry (the measurements are made by OK Laboratorium for Jordbrug in Viborg on behalf of Samson Bimatech). Thereby it is ensured that a realistic composition of the fiber fraction has been established. The liquid fraction is then calculated as the difference between the reference slurry and the fiber fraction. This means that the water content of the liquid fraction will be lower than the measurements by Samson Bimatech (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 and C, the water content (not the concentration) is relatively unimportant for the overall results.

Accordingly, a new theoretical calculation of the mass is needed. As the “Norm Data slurry” contains 69.7 kg DM and the fibre fraction (after separation) contains 396.9 kg DM per 1000 kg fibre fraction, a separation of the “Norm Data fattening pig slurry” will lead to 51.98 kg fibre fraction² and 948.02 kg liquid fraction³.

The calculations for the separation are shown in table C.3.

The calculations in table C.3 are based on a combination of the measured values of the fibre fraction after separation and the separation indexes from table C.2.

The DM is split between the fibre fraction and the liquid fraction in accordance with the separation index in table C.2, i.e. 29.8% of the DM is transferred to the fibre fraction (and the rest to the liquid fraction). From this, it is calculated that 0.37 kg DM ends in the fibre fraction⁴.

The slurry content of N is split between the fibre fraction and the liquid fraction in accordance with the separation index in table C.2, i.e. 6.8% of the N is transferred to the fibre fraction (and the rest to the liquid fraction). From this, it is calculated that 0.37 kg N ends in the fibre fraction⁵. This corresponds to a concentration of 7.17 kg N per 1000 kg fibre fraction⁶. The measurements of the fibre fraction from the piglet slurry showed a content of total-N of 8.8 kg N per 1000 kg fibre fraction. The difference is in

² The Norm Data slurry contains 69.7 kg DM. 29.6% of the DM ends up in the fibre fraction (see table C.2) i.e. $69.7 \text{ kg} * 29.6\% = 20.63 \text{ kg DM}$. As the fibre fraction contains 396.9 kg DM per 1000 kg fibre fraction (due to measurements), the total amount of fibre fraction is: $20.63 \text{ kg DM} / (396.9 \text{ kg DM per } 1000 \text{ kg fibre fraction}) = 51.98 \text{ kg fibre fraction}$.

³ $1000 \text{ kg slurry} - 51.98 \text{ kg fibre fraction} = 948.02 \text{ kg liquid fraction}$.

⁴ The Norm Data Slurry contains 69.7 kg DM ex housing. 29.6% of this ends in the fibre fraction according to the separation index in table C.2.
 $69.7 \text{ kg DM} * 6.8\% = 0.373 \text{ kg N}$.

⁵ The Norm Data Slurry contains 5.48 kg N ex housing. 6.8% of this ends in the fibre fraction according to the separation index in table C.2.
 $5.48 \text{ kg N} * 6.8\% = 0.373 \text{ kg N}$.

⁶ $0.373 \text{ kg N} / 51.98 \text{ kg fibre fraction} * 1000 \text{ kg} = 7.17 \text{ kg N per } 1000 \text{ kg fibre fraction}$.

correspondence with the fact that the Norm Data contains less total N per kg DM (7.9 kg N per kg DM) compared to the measured data for the piglet slurry (9.7 kg N per kg DM). The difference is within the differences that can be found in real life between various slurry samples.

The slurry content of P is split between the fibre fraction and the liquid fraction in accordance with the separation index in table C.2, i.e. 9.1% of the P is transferred to the fibre fraction (and the rest to the liquid fraction). From this, it is calculated that 0.10 kg P ends in the fibre fraction⁷. This corresponds to a concentration of 1.98 kg P per 1000 kg fibre fraction⁸. The measurements of the fibre fraction from the piglet slurry showed a content of phosphorous of 1.76 kg P per 1000 kg fibre fraction. The difference is within the differences that can be found in real life between various slurry samples.

The slurry content of K is split between the fibre fraction and the liquid fraction in accordance with the separation index in table C.2, i.e. 2.9% of the K is transferred to the fibre fraction (and the rest to the liquid fraction). From this, it is calculated that 0.083 kg K ends in the fibre fraction⁹. This corresponds to a concentration of 1.59 kg K per 1000 kg fibre fraction¹⁰. The measurements of the fibre fraction from the piglet slurry showed a content of phosphorous of 1.41 kg K per 1000 kg fibre fraction. The difference is within the differences that can be found in real life between various slurry samples.

A separation index for Cobber and Zink is taken from Møller et al (2007), see table C.2. These have been used for splitting Cu and Zn between the fibre fraction and the liquid fraction.

The composition of the fibre fraction is used to calculate the composition of the liquid fraction in table C.3. The composition of the liquid fraction is calculated as the difference between the content in the Norm Data slurry minus the content in the fibre fraction. Note that the amount of water is far too low in the liquid fraction, as mentioned above. The liquid fraction would normally contain 2-3% Dry Matter (personally correspondence, J Mertz, 2009).

⁷ The Norm Data Slurry contains 1.13 kg P ex housing. 9.1% of this ends in the fibre fraction according to the separation index in table C.2.
 $1.13 \text{ kg P} * 9.1\% = 0.10283 \text{ kg P}$.

⁸ $0.10283 \text{ kg P} / 51.98 \text{ kg fibre fraction} * 1000 \text{ kg} = 1.97826 \text{ kg P per 1000 kg fibre fraction}$.

⁹ The Norm Data Slurry contains 2.85 kg K ex housing. 2.9% of this ends in the fibre fraction according to the separation index in table C.2.
 $2.85 \text{ kg K} * 2.9\% = 0.083 \text{ kg K}$.

¹⁰ $0.083 \text{ kg K} / 51.98 \text{ kg fibre fraction} * 1000 \text{ kg} = 1.59 \text{ kg K per 1000 kg fibre fraction}$.

Table C.3.

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 i.e. "ex housing values from table A.1 in Annex A	Separation index from table C.2	Mass Balance: Amount transferred to the fibre fraction	Mass balance: Amount transferred to the liquid fraction	Composition of the fiber fraction AFTER separation Fibre fraction * 1000 / 51.98 kg	Composition of liquid fraction ^{b)} 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	Not used ^{a)}	51.98 kg ^{b)}	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.
- b) The calculation of the total mass is based on measurement 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 $20.63 \text{ kg} * 100/39.69 = 51.98 \text{ kg}$
- c) $\text{Total mass-DM} = 51.98 \text{ kg} - 20.63 \text{ kg} = 31.35 \text{ kg}$

In table C.4 the life cycle inventory data for mechanical separation can be seen. It has not been possible to identify data on emissions from the process. It is assumed that the emissions from the storage of the fiber fraction after the separation process exceeds the emissions during the separation process itself. The lack of data is especially critically for emissions of ammonia, which is supposed to be emitted in significant amounts. It is roughly estimated that the amount of ammonia, that is emitted during separation would be emitted

anyway during storage at a later point. Sensitivity analysis for this assumption has been carried out.

Focus has been put on the attempt to find data on storage of the fiber fraction, see the next section.

The energy consumption for the mechanical separation is 0.95 kWh per 1000 kg pig slurry (Mertz, 2008). Møller et al. (2002) found an energy consumption for screw press separation at 0.90 kWh per 1000 kg pig slurry (and 1.1 kWh per 1000 kg cattle slurry), which is well in accordance with the data from Samson Bimatech. Møller et al. (2000) found an energy consumption of 0.53 kWh per 1000 kg cattle slurry for a “pressing screw separator” which is regarded as within the uncertainty range of the data.

Table C.4.

Life cycle data for mechanical separation (Samson Bimatech). 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 under the pig housing units. This is the reference amount of slurry, i.e. the emissions are calculated relative to this.
Output		
Fibre fraction	52 kg	
Liquid fraction	948 kg	Reject slurry / liquid phase of the slurry
Energy consumption		
Electricity	0.95 kWh	Reference: Personal communication, J. Mertz, 2008.
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. Sensitivity analysis carried out for this.
Nitrous oxide (N ₂ O-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 ₂ S)		No data
Sulphur dioxide (SO ₂)		No data
Odour		No data
Emissions to water		
		No emissions to water

A list of the materials used in for the construction of the mechanical separation plant is shown in table C.5. The consumption is based on qualified expert estimates.

Table C.5
Material consumption and for the mechanical separation 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]
Separation Plant ¹⁾					
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 ²⁾					
Steel	50 kg	1 years	15000 m ³ / y	15000 m ³	3.3 g
Filter for screw press ³⁾					
Steel	6.5 kg	0.5 year	15000 m ³ / y	7500 m ³	0.86 g

The density of slurry roughly 1000 kg per m³ used for these estimates (as it is rough estimates anyway).

C.5 Outdoor storage of the liquid fraction

The outdoor storage of the liquid fraction is assumed to be identical to the outdoor storage of the untreated slurry in Annex A, adjusted by the relative ratio of N and C in the liquid fraction compared to the untreated slurry in Annex A. For a description of the assumptions and references, see Annex A.

This process included the energy consumptions for:

- Stirring slurry in the outdoor concrete tank when straw is added (pig slurry only)
- Stirring slurry before pumping from outdoor storage tank.
- Pumping slurry from the storage tank to the transport tank.

The energy consumptions are shown in table C.6. See further description in Annex A.

Table C.6
Energy consumption for stirring and pumping slurry during storage. All data per 1000 kg of slurry "ex housing".

	Fattening pig slurry
Electricity for stirring in the outdoor concrete tank when straw is added (pig slurry only)	1.2 kWh
Electricity for stirring in the outdoor concrete tank before pumping to transport container.	1.2 kWh
Electricity for pumping from the storage tank to the transport container.	0.5 kWh
Total	2.9 kWh

Table C.7

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 from fattening pigs (scenario C)	Comments
Input			
Slurry "ex separation"	1000 kg		The emissions are calculated relative to this.
Concrete slurry store	Included		As in scenario A.
Output			
Slurry "ex storage"	1086 kg		As mass balance from scenario A.
Energy consumption			
	Not included here		No energy consumption. Energy consumption for pumping and stirring is included under the process "Pumping and stirring"
Emissions to air			
Carbon dioxide (CO ₂)	0.18 kg	0.13 kg	Scenario A: 0.18 kg 0.18 kg * 24.7 kg (C in liquid fraction) / 33.3 kg (C in ex housing slurry in scenario A) = 0.13 kg
Methane (CH ₄)	1.94 kg	1.44 kg	Scenario A: 1.94 kg 1.94 kg * 24.7 kg (C in liquid fraction) / 33.3 kg (C in ex housing slurry in scenario A) = 1.44 kg
Ammonia (NH ₃ -N)	0.11 kg	0.11 kg	The total-N in the reference slurry ex housing is 5.48 kg per 1000 kg slurry. The total-N in the liquid fraction ex separation is 5.39 kg per 1000 kg liquid fraction. The difference of the N content in the reference slurry "ex housing" from scenario A and the N content in the liquid fraction is less than 2%. Accordingly, the emissions are assumed to be identical for the two scenarios.
Direct emissions of Nitrous oxide (N ₂ O-N)	0.033 kg	0.033 kg	
Indirect emissions of Nitrous oxide (N ₂ O-N)	0.0014 kg	0.0014 kg	
Nitrogen monoxide (NO-N) (representing total NO _x)	0.033 kg	0.033 kg	
Nitrogen dioxide (NO ₂ -N)	No data	No data	
Nitrogen (N ₂ -N)	0.099 kg	0.099 kg	
Discharges to water			
	None		Assumed to be none, as leakages from slurry tanks are prohibited in Denmark

The composition of the liquid fraction after storage is shown in table C.8. Note that the amount of water is far too low in the liquid fraction, as mentioned above.

Table C.8.

Mass balances for storage of the liquid fraction after mechanical separation of slurry from fattening pigs.

	Composition of liquid fraction before storage (from table C.2) [kg per 1000 kg liquid fraction]	Mass balance: Change during storage [kg]	Mass balance: Amount after storage [kg]	Composition of liquid fraction after storage ^{a)} [kg per 1000 kg liquid fraction]
Total mass	1000 kg liquid fraction BEFORE storage	+ 86 kg (as in Annex A)	1086 kg	1000 kg liquid fraction after storage
Dry matter (DM)	51.76 kg	- 1.864 kg ^{d)}	49.9 kg	45.9 kg
Total-N	5.387 kg	- 0.275 kg ^{b)}	5.11 kg	4.71 kg
Total-P	1.0833 kg	None	1.09 kg	1.00 kg
Potassium (K)	2.9187 kg	None	2.92 kg	2.69 kg
Carbon (C)	24.728 kg	-1.114 kg ^{c)}	23.6 kg	21.745 kg
Copper (Cu)	30.189 g	None	30.189 g	0.0278 kg
Zinc (Zn)	88.361 g	None	88.361 g	0.08136 kg

a) Calculated by dividing with the mass of the liquid fraction i.e. 1000 kg / 1086 kg

b) Emissions: 0.11 kg NH₃-N + 0.033 kg kg N₂O-N + 0.033 kg NO + 0.099 kg N₂ = 0.275 kg

c) Emissions: 0.13 kg CO₂ * 12.011 / 44.0089 + 1.44 kg CH₄ * 12.011 / 16.04 = 1.114 kg C

d) Assumption for DM: 80% is VS, the loss of VS corresponds to the relative loss of C, i.e. 1.114 kg C/24.728 kg C = 4.5%. Loss = 51.8 kg * 80% * 4.5% = 1.864 kg

C.6 Transport of the 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.

C.7 Field processes (liquid fraction)

The emissions from the field processes are calculated relative to the emissions from the reference slurry in scenario A. The life cycle data for the field processes are shown in table C.9.

In order to calculate N leaching values, the simplifying assumption that the liquid fraction, once the respective ammonia losses have been subtracted, can be equaled by a predominant proportion of slurry, and a smaller amount of mineral N, as in mineral fertiliser as the liquid fraction has a higher content of N relative to C, than the original reference slurry (as the mechanical separation separates relatively more C to the fibre fraction (i.e. 29.6%) than N (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 basis 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 pig 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 are therefore the basis for the calculation of N leaching, after correcting for their respective ammonia volatilizations.

According to Hansen et al. (2008), the ammonia volatilization from the liquid fraction from separated slurry applied to fields is reduced significantly – 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. Hence, the volatilization of ammonia from the applied liquid fraction stops faster than for untreated slurry. Measurements were made on mechanically separated slurry (untreated and degassed slurry), and the liquid fraction / slurry were applied by trail hoses. The measurements showed that the ammonia emissions were reduced by approximately 50% (Hansen et al., 2008).

As discussed above, the liquid fraction from mechanical separation of the reference slurry in this study has a DM content that is unrealistic high due to too small amounts of water in the Danish Norm Data for slurry. However, for a realistic scenario, the liquid fraction from the mechanical separation would have a DM content of less than 3%, as presumed in Hansen et al. (2008). Measurements from the Samson Bimatech plant show that the liquid fraction contains 2-3.5% DM after separation (Personal communication, J Mertz, 2008). It means: In spite of the theoretical calculations for mechanical separation of the “Danish Norm Data slurry”, it has been assumed that the experience by Hansen et al. (2008) also applies for the reference slurry, as it has been acknowledged that there should have been a higher water content – and hence, that the DM content should have been lower. Accordingly, it is assumed that the ammonia emissions are reduced by 50% as indicated by Hansen et al. (2008). It is assumed that it applies for ammonia emissions in period after application only, i.e. *not* for the ammonia emissions during application – due to the explanation above.

Table C.9.

Life cycle data for application of the liquid fraction and field processes (scenario C). All data per 1000 kg of slurry, resp. liquid fraction ex outdoor storage.

	Reference pig slurry (scenario A)	Liquid fraction from fattening pigs (scenario C)	Comments
Input			
Slurry "ex storage"	1000 kg	1000 kg	Slurry 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: See Annex A	Fertiliser replacement value: See Annex D and E	The fertiliser value of this slurry results in subtraction of mineral N, P and K N fertiliser value – Depends on the utilisation of the fibre fraction. See the subsequent Annexes.
Energy consumption			
Diesel for slurry	0.4 litres of diesel	0.4 litres of diesel	As in scenario A.
Emissions to air			
Carbon dioxide (CO ₂)			Modelled by C-TOOL (Gyldenkærne et al, 2007). 10 year value and 100 year in parenthesis
Soil JB3	81.6 (99.8) kg	56.2 (73.562) kg	
Soil JB6	80.2 (99.4) kg	55.1 (73.142) kg	
Methane (CH ₄)	Negligible	Negligible	As in scenario A.
Ammonia (NH ₃ -N) during application	0.02 kg	0.02 kg	NH ₃ emissions during application: 0.5% of NH ₄ +N "ex storage" Hansen et al. (2008). N ex storage = 4.71 kg
Ammonia (NH ₃ -N) in period after application	0.48 kg	0.24 kg	NH ₃ emissions in the period after application are based on Hansen et al. (2008) and the current slurry distribution in the crop rotation, see Annex A. 50% of this for liquid fraction, see above (Hansen et al., 2008).
Direct emissions of Nitrous oxide (N ₂ O-N)	0.05 kg [0.015-0.15]	0.05 kg [0.015-0.15]	0.01 [0.003 - 0.03] kg N ₂ O-N per kg N "ex storage" for application of animal wastes to soil, based on IPCC (2006, table 11.1).
Indirect emissions of Nitrous oxide (N ₂ O-N)	0.005 kg	0.005 kg	Indirect emissions due to emissions of ammonia and NO _x : 0.01 kg N ₂ O-N per kg (NH ₃ -N + NO _x -N) volatilised (IPCC, 2006)
Soil JB3	0.014 kg	0.014 kg	Indirect emissions due to nitrate leaching: 0.0075 kg N ₂ O-N per kg N leaching (IPCC, 2006).
Soil JB6	0.011 kg	0.011 kg	
Nitrogen oxides (NO _x -N)	0.005 kg	0.005 kg	NO _x -N = 0.1 * N ₂ O-N according to Nemecek and Kägi (2007)
Nitrogen (N ₂ -N)			Estimated from the SimDen model ratios between N ₂ O and N ₂ by Vinther (2005), see text.
Soil JB3	0.15 kg	0.15 kg	
Soil JB6	0.30 kg	0.30 kg	
Discharges to soil			
Nitrate leaching			Estimated from N partitioning tables A.15 and A.16 as explained in text. 10 year values, numbers in parenthesis are 100 year values.
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	0.113 kg P	0.10 kg P	10% of the P applied to field (Hauschild and Potting, 2005 – only 6% of this reach the aquatic environment, see text).
Copper (Cu)	0.0276 kg	0.027 kg	See table A.18 and C.8
Zinc (Zn)	0.0824 kg	0.0856 kg	See table A.18 and C.8

C.8 Avoided mineral fertilisers

The calculation of the fertiliser replacement value for N in the liquid fraction depends on the utilization of the fibre fraction. If, for example, the fibre fraction is combusted, the amount of N in the liquid fraction of the slurry replace mineral N fertiliser by 85% according to Danish Law (Gødskningsbekendtgørelsen, 2008, and Gødskningsloven, 2006) as described in Annex D.

Accordingly, the fertiliser replacement value for the liquid fraction is calculated in each of the subsequent Annexes (D and E).

Annex D. Fibre Pellets combusted in Energy Plant – Life Cycle Inventory data

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D.1 System description

This annex contains Life Cycle Inventory data for fibre pellet production in a Samson Bimatech Plant MaNergy 225 producing heat from the fibre pellets.

The fibre pellets are produced in a number of steps, which include mechanical separation of pig slurry, drying of the fibre fraction and pressing the dried fibres into pellets. The pellets can be used for heat production at the farm in a Samson Bimatech Energy Plant. The heat production demands that the farmer needs the heat for heating, for example his private house or the housing units for farrowing sows with piglets. The phosphorus is left in the ash from the combusted fibre pellets might be used on the fields as fertiliser. The drying process of the wet fibres requires heat consuming app. 40 % of the energy from the fibre pellets. The Energy plant is described in section D.4.

Alternatively, the fibre pellets could be applied directly to the field as fertiliser utilizing the N, P and K content. This possibility is covered in Annex E.

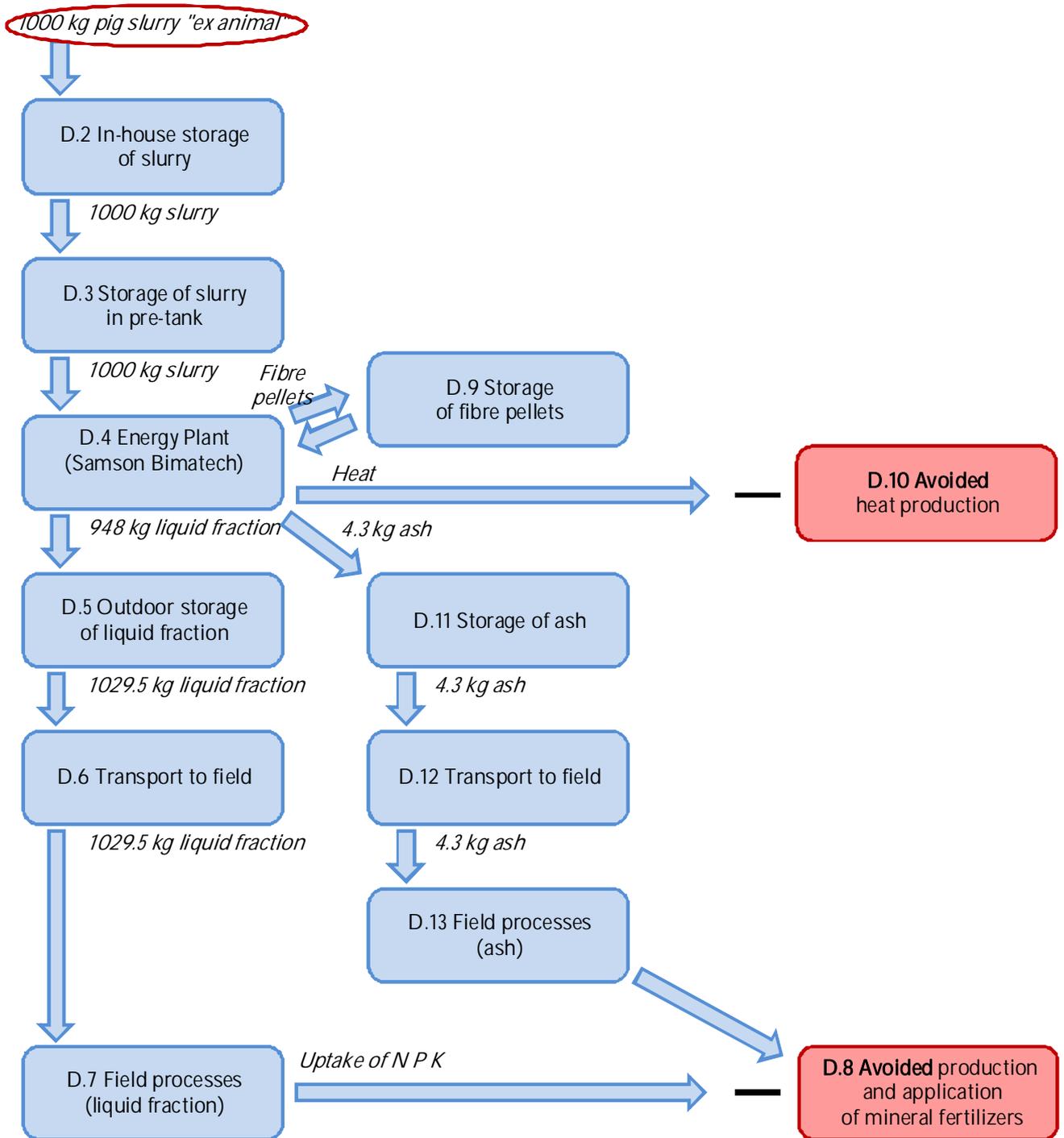
The fibre pellets might also be transported to a central biogas plant and used for combined heat and power production. This possibility is covered in a following study.

The fibre pellets might also be used as fuel in central power plants. However, this opportunity is not covered in this study.

Samson Bimatech also produces a “stand-alone” mechanical separation plant, which is described in Annex C.

The scenario containing the Energy Plant producing energy based on fibre pellets is shown in figure D.1. The process numbers refer to the heading of the section in this Annex D.

Figure D.1.
Flow diagram for the scenario with the Samson Bimatech Energy Plant (Annex D).



D.2 In-house storage of slurry

This process is identical to process C.2 in Annex C.

D.3 Storage of slurry in pre-tank

This process is identical to process C.3 in Annex C.

D.4 Energy plant

The processes in the energy plant are:

- Separation of the slurry into a fibre fraction and liquid fraction
- Drying of fibres in a tumble dryer
- Pellet production
- Combustion in gasifier and furnace and heat exchange in a boiler

The fibre pellet production starts by mechanical separation of the pig or cattle slurry. The fibre fraction is dried in a tumble dryer, and the dried, warm fibre fraction is then pressed into pellets. The pellets are cooled before storage for avoiding condensation in the outdoor silo.

In this Annex it is assumed that all the pellets are combusted in the Energy Plant, giving energy that can be used for heating the farmer's private house. The consequence of the heat delivered is that the farmer saves energy for heating. Accordingly, this avoided heating is subtracted from the system. The nitrogen is transformed to N_2 and the phosphorus is left in the ash and might be used on the fields as fertiliser.

The flow diagram for energy plant is shown in figure D.2. The processes in the combustion plant are shown in figure D.3.

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 not loss or emissions during the storage in the pre-tank. As discussed in Annex C, this is a rough estimate as there is significant biological activity in the pre-tank and in the slurry system below the stables.

As the Samson Bimatech Energy Plant is based on the same mechanical separation as in Annex C, the mass balances for the separation are established in Annex C. In the Energy Plant, fibre pellets are produced from the fibre fraction from the mechanical separation.

Figure D.2.
Flow diagram for Samson Bimatech energy plant.

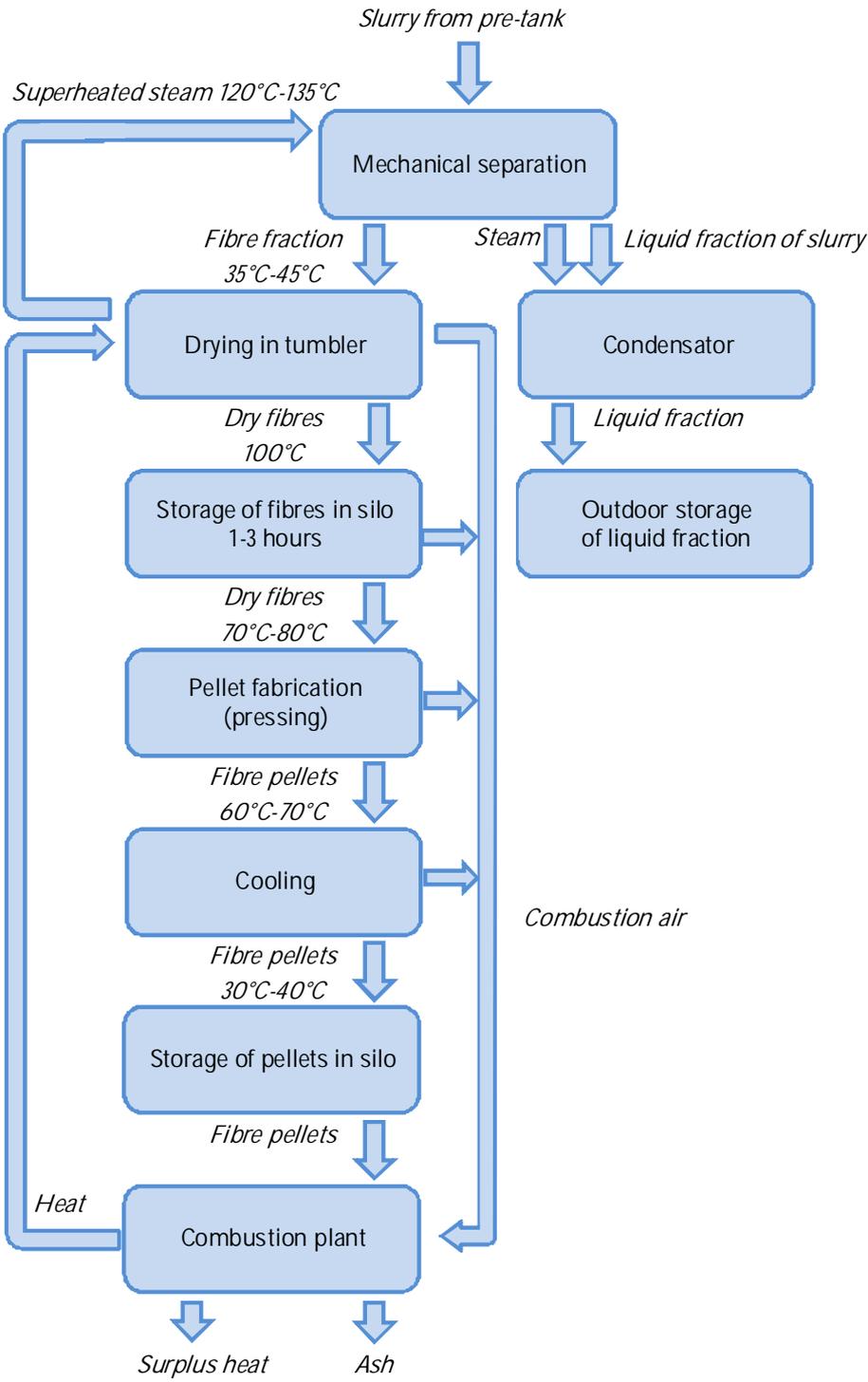
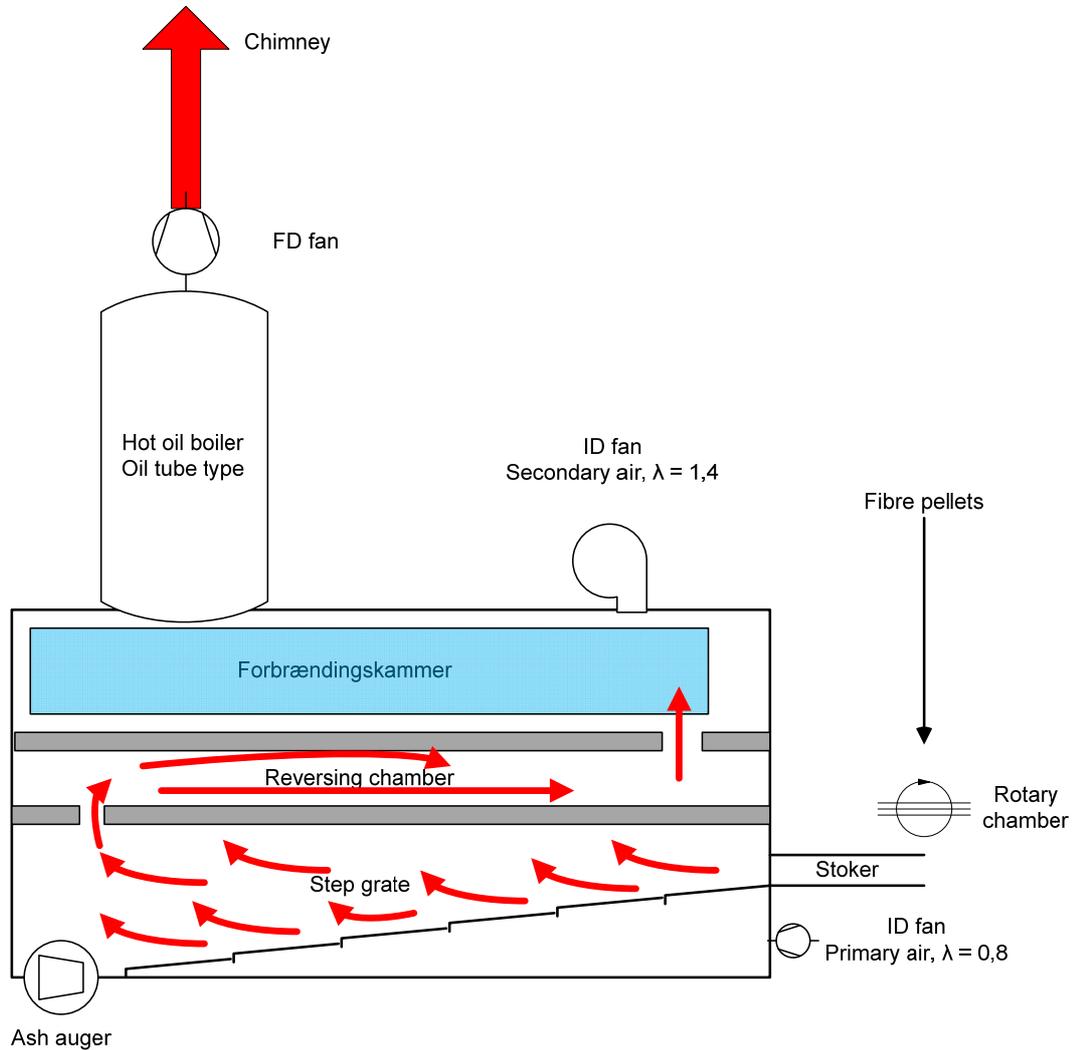


Figure D.3.
Principles for the Samson Bimatech energy plant



The electricity consumption for the plant corresponds to 19 kWh per 1000 kg pig slurry. The electricity is used for pumps, the screw separator, pellet machine (biggest motor in the plant) and other electric devices. This consumption is exclusive of stirring. The energy for drying the fibres comes from the heat production from the plant, corresponding to 120 MJ per 1000 kg slurry. The energy needed for heating and evaporating the water in the fibre fraction corresponds to 77 MJ per 51.98 kg fibre fraction (which corresponds to 1000 kg slurry) ¹. Accordingly, the energy for drying the

¹ As can be seen below, 1000 kg of slurry corresponds to 51.98 kg fibre fraction. The fibre fraction has a DM content of 39.69%, i.e. water content of 60.31%. $51.98 \text{ kg} * 60.31\% = 31.35 \text{ kg water per 1000 kg slurry}$.

As can be seen below, 1000 kg of slurry corresponds to 23.19 kg fibre pellets with 88.93% DM, i.e. 11.07% water, i.e. a water content of $23.19 \text{ kg} * 11.05\% = 2.57 \text{ kg water per 1000 kg slurry}$.

The water that needs to be evaporated is $31.35 \text{ kg} - 2.57 \text{ kg} = 28.78 \text{ kg}$

All the water is assumed to be heated from 10°C to 100°C.

Energy for heating water:

fibres seems as a reasonable conservative estimate (when including the fact that a considerable amount of the heat is wasted to the surroundings.).

The amount of surplus heat produced is 128 MJ per 1000 kg slurry. The pellets works a “energy storage” – at winter time, they are all combusted for producing heat for the farmers private house, at summer time, the plant only produce the heat needed for drying the fibres, producing pellets that can be stored for next winter. All data are based on information from Samson Bimatech (personal communication with J Mertz, 2009).

It is assumed that all the heat is used at the farm. Calculation example: A farm with a production of 1400 fattening pigs per year (farm type 20 from Dalgaard et al., 2008, paper 3), with a production of 0.47 tons slurry per fattening pig the surplus heat production is in the magnitude of 84000 MJ per year².

The heat consumption of a Danish household varies a lot with the age of the house, the insulation of the house and the number of people in the household. An estimate, based on data from Dong Energy (2009) shows that the heat consumption of an average Danish household is in the order of 46400-102000 MJ per year, assuming a house of 140 m² and a family of 4 persons³. Accordingly, the slurry production from 1400 fattening pigs should be able to produce the heat needed for a family of 4 in a 140 m² house (build before 1962 and with some insulation) or for a larger house (if it is newer or the insulation is better) or for a family with 5-6 persons. The rough estimates show that the heat produced by the pig slurry probably is at the same magnitude as the need for heat by the farmer and his family.

The uncertainty on the measurements is considered to be rather high, as the emissions and energy production to a great degree depend on the actual slurry composition, and as it has not been possible to construct a “Norm Data Slurry” for testing in real life.

31.35 kg * 4.187 kJ/kg°C * (100°C-10°C) / 1000 MJ/kJ= 11.8 MJ
Energy for evaporating water: 28.78 kg * 2.26 MJ/kg = 65 MJ
Total energy consumption: 65 MJ + 11.8 MJ = 76.8 MJ

² 1400 fattening pigs * 470 kg slurry per year * 128 MJ / 1000 kg slurry = 84000 MJ per year.

³ According to Dong Energy (2009)

<http://www.dongenergy.dk/privat/energiforum/tjekditforbrug/typisk%20varmeforbrug/Pages/fjernvarme.aspx> the heat consumption is in the order of:

200 kWh per m² per year for houses build before 1962 – and no insulation

170 kWh per m² per year for houses build before 1977 – and no insulation

110 kWh per m² per year for houses build after 1977

90 kWh per m² per year for houses build after 1998

The heat consumption for hot water (showers and hygiene) is in the order of 75 kWh per person per year.

Assuming 4 persons in the household, 140 m² house, old house, no insulation:

4 persons * 75 kWh/person + 140 m² * 200 kWh per m² per year = 28300 kWh = 101880 MJ per year.

Assuming 4 persons in the household, 140 m² house, new house:

4 persons * 75 kWh/person + 140 m² * 90 kWh per m² per year = 12900 kWh = 46440 MJ per year.

The above data corresponds to an Energy Plant where all the fibre pellets are used for combustion within the plant.

According to personal communication with J Mertz (2009), measurements of the emissions from the Energy Plant correspond to:

- 45 kg carbon dioxide (CO₂) per 1000 kg pig slurry
- 0.071 kg carbon monoxide (CO) per 1000 kg pig slurry
- 0.104 kg nitrogen oxides (NO_x) per 1000 kg pig slurry
- 0.0295 kg particulates (dust)

However, when using the mass balances, the combustion of the “reference pig slurry” based on the Norm Data pig slurry in this study, the CO₂ emission is 36.13 kg per 1000 kg slurry⁴, which is used in this study. The measurements by Samson Bimatech are made for at different slurry composition than the reference slurry in this study.

During drying of the fibres, ammonia (NH₃) volatiles. The air from the “drying tumbler” is sent to the combustion in the furnace, where it is combusted to nitrogen (N₂). Some of the ammonia (NH₃) is also absorbed by the liquid slurry fraction. The fraction that goes to the liquid fraction vs. the fraction that is combusted to N₂ in the furnace is not known. However, NH₃ is not emitted to the environment in significant amounts. There will probably be small amounts of NH₃ emissions (as no plant is 100% tight), however, the amounts are assumed to be insignificant compared to the emissions from the storage of slurry due. The assumption is supported to the fact that when being in the Energy Plant or outside the Energy Plant, the NH₃ odour is not strong – and by no means as strong as from the pre-tank or in the housing units.

The N₂ emissions are based on mass balances. According to Hjort-Gregersen and Christensen (2005) all nitrogen is emitted when the solid fraction is incinerated.

As described in the calculation for table C.3 in Annex C, the separation of the “Norm Data fattening pig slurry” will lead to 51.98 kg fibre fraction. The fibre fraction is heated and dried. It is assumed that the content of DM is not reduced during this process.

The fibre pellets has a varying content of DM and water, depending on the original raw slurry. In this study, data is based on measurements from “real life fibre pellets” produced on slurry from piglets. No data has been available on slurry from fattening pigs. The fibre pellets contain 88.93% DM (measurements performed by OK Laboratorium for jordbrug, 03-03-2009). Accordingly, 1000 kg of “Norm data” pig slurry “ex animal” gives 51.98 kg fibre fraction, leading to 23.199 kg fibre pellets⁵. This corresponds to 20.62 kg DM.

⁴ As can be seen from table C.3 in Annex C, the fibre fraction from the separation contains 9.86 kg C per 1000 kg slurry. If all this is combusted to CO₂ the maximum CO₂ emission is: 9.86 kg * 44.01 g/mol / 12.01 g/mol = 36.13 kg CO₂. An insignificant part of this becomes CO.

⁵ 1000 kg slurry gives 51.98 kg fiber fraction * 39.69% DM = 20.62 kg DM
The amount of fibre pellets can then be calculated to: 20.62 kg * 1000 kg / 889.3 kg DM per 1000 kg = 23.199 kg fiber pellets per 1000 kg slurry.

The ash content of the fibre pellets correspond to 0.209 kg ash per kg DM. Accordingly, combustion of the fibre pellets from 1000 kg “Norm Data” pig slurry gives 4.3 kg ash (= 20.62 kg DM * 0.209 kg ash per kg DM).

Data on the loss of N during heating and pressing the fibre fraction into fibre pellets has not been available. Instead the theoretical loss of N has been calculated as the difference between the N in the fibre fraction (Norm data) and the fibre pellets (measurements). This is a rough approximation. The fibre fraction contains 0.37 kg N (per 1000 kg slurry) (see table C.3 in Annex C and table D.1 below). The measured fibre pellets contain 11.59 kg N per 1000 kg fibre pellets, i.e. 0.27 kg N per 1000 kg slurry⁶. Accordingly, 0.1 kg N seems to be lost during the fibre pellet production. This loss of N is at the same magnitude as when calculation the loss from “measured fibre fraction” to “measured fibre pellets”. It is assumed that the loss of N is lost as NH₃ but as the air from the heating and fiber pellet pressing is gathered within the plant and used as combustion air for the combustion plant, the amounts of NH₃ is converted to NO_x and N₂ during the combustion.

When the fibre pellets are combusted, all N in the fibre pellets is emitted as NO_x or N₂. The ash do not contain N (at least not in significant amounts). The emissions of N₂ is calculated as the difference between total loss of N and the NO_x emissions to 0.355 kg N₂⁷.

⁶ 11.59 kg N per 1000 kg fibre pellets * 23.187 kg fibre pellets / 1000 kg slurry = 0.27 kg N per 1000 kg slurry.

⁷ The amount of N in the fibre fraction corresponds to 0.37 kg N per 1000 kg slurry, see table D.1. Of these, 0.015 kg N is emitted as NO_x, see text above. The rest: 0.37 kg N - 0.015 kg N = 0.355 kg N is assumed to be lost as N₂.

Table D.1.

Mass balances for mechanical separation of pig slurry and fibre pellet production from **fattening pigs**. Per 1000 kg of slurry "ex housing".

	Amount in slurry Ex pre-tank BEFORE separation (see table C.3 in Annex C) [kg]	Mass balance: Amount in fibre fraction in 51.98 kg fiber fraction after separation (see table C.3 in Annex C) [kg]	Mass balance: Amount in fibre pellets after drying	Composition of fibre pellets based on theoretical calculation ^c	Concentration in fibre pellets based on measurements [kg per 1000 kg fibre pellets]
Total mass	1000 kg Slurry Ex pre-tank	51.98 kg	23.199 kg ^b	1000 kg	1000 kg
Dry matter (DM)	69.7 kg	20.63 kg	20.63 kg	889.3 kg	889.3 kg
Total-N	5.48 kg	0.37 kg	0.37 kg – 0.1 kg = 0.27 kg ^a	11.75 kg	11.59 kg
Total-P	1.13 kg	0.1028 kg	0.1028 kg	4.433 kg	1.76 kg
Potassium (K)	2.85 kg	0.08265 kg	0.08265 kg	3.563 kg	3.08 kg
Carbon (C)	33.3 kg	9.857 kg	9.857 kg	424.88 kg	
Copper (Cu)	30.0 g	1.38 g	1.38 g	0.0595 kg	
Zinc (Zn)	89.4 g	5.63 g	5.63 g	0.2428 kg	

^a Loss of N, see text.

^b See text above

^c The values in the column "Amount in fibre pellets after drying" divided by the mass, i.e. 1000 kg / 23.199 kg.

For a range of the emissions, data has not been available. It is assumed that the methane (CH₄) emissions are insignificant, as they are mainly caused by biological activity.

It is likely that some of the easy degradable fatty acids evaporate during the drying process, reducing the content of VS and DM in the fibre fraction. It has not been possible to find data on this.

The life cycle data for the Energy Plant are shown in table D.2

Table D.2.

Life cycle data for treatment of slurry in the Samson Bimatech energy. Data per 1000 kg slurry treated.

	Fattening pig slurry	Comments
Input		
Slurry (ex pre-tank)	1000 kg	Slurry directly from the pre-tank under the pig housing units. This is the reference amount of slurry, i.e. the emissions are calculated relative to this.
Output		
Fibre pellets	None	In this Annex, all fibre pellets are used for heat production in the Energy Plant.
Liquid fraction of the slurry	948 kg	Reject slurry / liquid phase of the slurry
Ash	4.3 kg	
Heat production, surplus.	128 MJ	Surplus heat can be used for heating the farmers privat house
Heat production used in the plant	120 MJ	Used in the plant for drying fibres, see 3 lines below
Energy consumption		
Electricity	19 kWh	Personal correspondence with J Mertz, 2009.
Heat	120 MJ	Used in the plant for drying fibres, produced by the plant, see 3 lines above
Wooden pellets	0.078 kg	Wooden pellets are used for heating when starting the plant.
Consumption of materials and chemicals		
Wooden pellets	0.078 kg	For starting the process
Emissions to air		
Carbon dioxide (CO ₂)	36.13 kg	Information from J. Mertz (2009)
Carbon monoxide (CO)	0.071 kg	Information from J. Mertz (2008)
Methane (CH ₄)	No data	Assumed to be negligible.
Non-methane volatile organic compounds (NMVOC)	No data	
Ammonia (NH ₃ -N)	-	Assumed to be insignificant.
Nitrous oxide (N ₂ O-N)	No data	
Nitrogen oxides (NO _x)	0.104 kg	Information from J. Mertz (2009)
Nitrogen(N ₂)	0.355 kg	Calculated according to mass balances, see text.
Particulates	0.0295 kg	Information from J. Mertz (October 2008) Size of the particulates not specified.
Hydrogen sulphide (H ₂ S)	No data	
Sulphur dioxide (SO ₂)	No data	
Odour	No data	
Emissions to water		
No emissions to water		

The theoretical composition of the ash after combustion of the fibre pellets in the energy plant is shown in table D.3. As mentioned above, all nitrogen is emitted when the solid fraction is incinerated (Hjort-Gregersen and Christensen, 2005). As can be seen, it has not been possible to estimate the DM and the total mass of the ash. However, as the ash is just added to the liquid fraction and applied to the field, it is only important to know the amount of P, K and Cu and Zn in order to estimate the amount of these added to the field.

Table D.3.

Mass balances for calculating the composition of the ash. Per 1000 kg of slurry "ex housing".

	Mass balance:	Mass balance:	Composition of ash
	Amount in fibre pellets after drying Per 1000 kg pig slurry ex animal	Amount in ash after combustion Per 1000 kg pig slurry ex animal	Per 1000 kg ash
Total mass	23.199 kg	4.312 kg	1000 kg
Dry matter (DM)	20.63 kg	4.312 kg	1000 kg
Total-N	0.2726 kg	0 kg	0 kg
Total-P	0.10283 kg	0.10283 kg	23.85 kg
Potassium (K)	0.08265 kg	0.08265 kg	19.17 kg
Carbon (C)	9.8568 kg	0 kg	0 kg
Copper (Cu)	1.38 g	1.38 g	0.32 kg
Zinc (Zn)	5.63 g	5.63 g	1.31 kg

A list of the materials used in for the construction of the Samson Bimatech Energy Plant, container and silo for storing the pellets are shown in table D.4. The consumption is based on rough estimates.

Table D.4

Material consumption and for the energy 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]
Energy Plant					
Steel	10 000 kg	30 years	10000 m ³ / y	300000 m ³	33 g
Concrete	10 000 kg	30 years	10000 m ³ / y	300000 m ³	33 g
Extruded polystyrene in walls	200 kg	30 years	10000 m ³ / y	300000 m ³	0.66 g
PVC in walls	200 kg	30 years	10000 m ³ / y	300000 m ³	0.66 g
Ovenproof materials, assumed to be magnesium oxide	500 kg	30 years	10000 m ³ / y	300000 m ³	1.7 g
Copper in cables	200 kg	30 years	10000 m ³ / y	300000 m ³	0.66 g
Electronics	7 kg - Assumed as 2 laptops	Assumption: 5 years	10000 m ³ / y	50000 m ³	4 E-5 laptops
Screw in screw press					
Steel	50 kg	1 year	10000 m ³ / y	10000 m ³	5 g
Filter for screw press					
Steel	6.5 kg	0.5 year	10000 m ³ / y	5000 m ³	1.3 g

The density of slurry roughly 1000 kg per m³ used for these estimates (as it is rough estimates anyway).

Note 1): Estimated life time: 30 years. 10000 m³ slurry per year = 300000 m³ slurry in a life time.

Note 2): Life time: 1 year. 10000 m³ slurry per year = 10000 m³ slurry in a life time

Note 3): Life time: 0.5 year. 10000 m³ slurry per year = 5000 m³ slurry in a life time

D.5 Outdoor storage of the liquid fraction

This process is identical to process C.5 in Annex C.

D.6 Transport of the liquid fraction to field

This process is identical to process C.6 in Annex C.

D.7 Field processes (Liquid fraction)

This process is identical to process C.7 in Annex C.

D.8 Avoided production of mineral fertilisers

The “fertiliser replacement value” for N is calculated for the total system is based on Danish Law combined with “common practice”.

First, the “fertiliser replacement value” for the reference system is stated (see Annex A for further details):

- Mineral N fertiliser: 5.00 kg N per 1000 kg slurry ex storage [the value given by the Danish Norm Data, as explained in Annex A] * 1086 kg slurry ex storage per 1000 kg slurry ex animal * 75% [the replacement value according to (Gødskningsbekendtgørelsen, 2008)] = 4.073 kg mineral N fertiliser
- Mineral P fertiliser: 1.04 kg P per 1000 kg slurry ex storage * 1086 kg slurry ex storage per 1000 kg slurry ex animal = 1.13 kg P
- Mineral K fertiliser: 2.60 kg K per 1000 kg slurry ex storage * 1086 kg slurry ex storage per 1000 kg slurry ex animal = 2.82 kg K

The “N fertiliser replacement value” for the “Energy Plant scenario” in this Annex is calculated as follows:

The amount of N in the liquid fraction of the slurry replace mineral N fertiliser by 85% according to Danish Law (Gødskningsbekendtgørelsen (2008), BEK 789, § 21⁸) when the fibre fraction is combusted. This 85% is different from the 75% used for the reference system above. Accordingly, 4.71 kg N [per kg liquid fraction after storage] * 948.02 kg liquid fraction after separation per 1000 kg slurry ex animal * 1086 kg liquid fraction ex storage per 1000 kg liquid fraction after separation * 85% = 4.122 kg N per kg slurry ex animal (i.e. for the total system) is replaced when the fibre fraction is combusted (see table C.8). This amount is almost identical to the mineral fertiliser value of the reference system (only 1% higher than for the reference system, 4.073 kg mineral N fertiliser).

⁸ BEK 786, § 21: Ved beregning af forbruget af kvælstof i husdyrgødning skal følgende andele af det totale indhold af kvælstof i gødningen anvendes: væskefraktion efter forarbejdning, hvor fiberfraktionen afbrændes: 85 pct

The system does not affect the total amount of P and K applied to field, as these are in the ash from the combusted fibre pellets, and as the ash is added to the liquid fraction at the farm before application (i.e. at the same farm).

D.9 Storage of fibre pellets

The fibre pellets are typically stored in 4-6 months, shorter during the winter period.

The fibre pellets are stored in a silo. During storage, the fibre pellets are protected against rain water, however, they might absorb moisture from the air.

Data for the emissions during storage of the fibre pellets has not been immediate available. It has been considered to initiate measurements of the emissions, however, due to the fact that the pellets are relatively dry (10-17% water), it is estimated that the biological decomposition is relatively low. According to E Fløjgaard Kristensen (2009), there is no decomposition in straw when the water content is lower than 15%.

As denitrification is restricted to environments without oxygen, denitrification will not take place.

As mentioned in Annex C, Hansen et al. (2006) measured the emissions from covered and uncovered heaps of separated fibre fraction (which has a higher water content). As can be seen in table C.10, the emissions from covered heaps are relatively low, only a few % of the initial values. As the emissions from the fibre pellets are likely to be lower due to the low water content, it is assumed that the emissions from storage of the fibre pellets are insignificant.

D.10 Avoided heat production

The produced heat is assumed to be used for heating the housing systems for the private housing units, and the consequence of this is that heat production is avoided. The avoided heat will vary depending on the other possibilities the farmer has in mind. Accordingly, two alternatives for the avoided heat production are calculated, one for a fuel oil boiler and another based on wood chips. The SimaPro processes chosen for the avoided heat is:

- Heat, light fuel oil, at boiler 10kW condensing, non-modulating
- Heat, wood pellets, at furnace 15kW

D.11 Storage of ash

The ash is stored in a covered / closed container. It is assumed that the emissions from storage of ash are insignificant. If handled careless or if it is not covered it will produce a lot of dust.

D.12 Transport of Ash to Field

Often, the ash is mixed with the liquid fraction of the slurry and applied to the local fields. However, the high content of P in the ash gives a possibility of transporting P from areas with excess P to areas with P deficiency. It is assumed that it is not being done right now as ash is not regarded as a valuable saleable fertiliser product in Denmark right now.

D.13 Field processes (ash)

According to Birkmose and Zinck (2008), P and K in the ash are less soluble in water than superphosphate. However, tests shows that the plant uptake of P from ash is at the same level as in mineral fertilisers. Birkmose and Zinck (2008) refers to a test where the conclusion where that P and K in ash from combusted chicken manure has a plant availability of 90-100% compared to mineral fertiliser. Accordingly, P and K will be calculated as replacing K and P mineral fertilisers 1:1.

The assumption has been questioned by members of the steering group of the project. It is beyond the scope and budget of the project to perform further analysis of the availability of the P in the ash. Further scientific research is needed in the area.

Sensitivity analysis has been performed for that the fertiliser value of the ash is 0.

As the ash does not contain N and C there will be no contributions to emissions of CO₂, CH₄ og N-compounds.

Table D.5.
Life cycle data for application of ash and field processes. All data per 1000 kg of slurry ex storage

	Fattening pig slurry	Comments
Input		
Ash from 1000 kg slurry ex storage	1000 kg ash	The emissions are calculated relative to 1000 kg slurry ex storage as the ash amount is not specified.
Tractor and slurry tanker		The tractor and slurry tanker is included under "diesel" below.
Output		
Liquid phase on field, fertiliser value	Fertiliser value: See section D.8	The fertiliser value of ash See section D.8
Energy consumption		
Diesel for slurry	Not included here	The diesel for application is assumed to be included in the application of the liquid fraction when the ash is mixed with this.
Emissions to air		
Carbon dioxide (CO ₂)	Negligible	
Methane (CH ₄)	Negligible	
Ammonia (NH ₃ -N)	Negligible	
Nitrous oxide (N ₂ O-N)	Negligible	
Nitrogen oxides (NO _x)	Negligible	
Odour	Negligible	[No data]
Discharges to soil		
Nitrate leaching		No N leaching as ash do not contain N
Phosphate leaching	2.385 kg P	10% of the P applied to field (Hauschild and Potting, 2005 – only 6% of this reach the aquatic environment, see text).
Copper (Cu)	0.32 kg	
Zinc (Zn)	1.3 kg	

Annex E. Pellet production for fertilising – Life Cycle Inventory data

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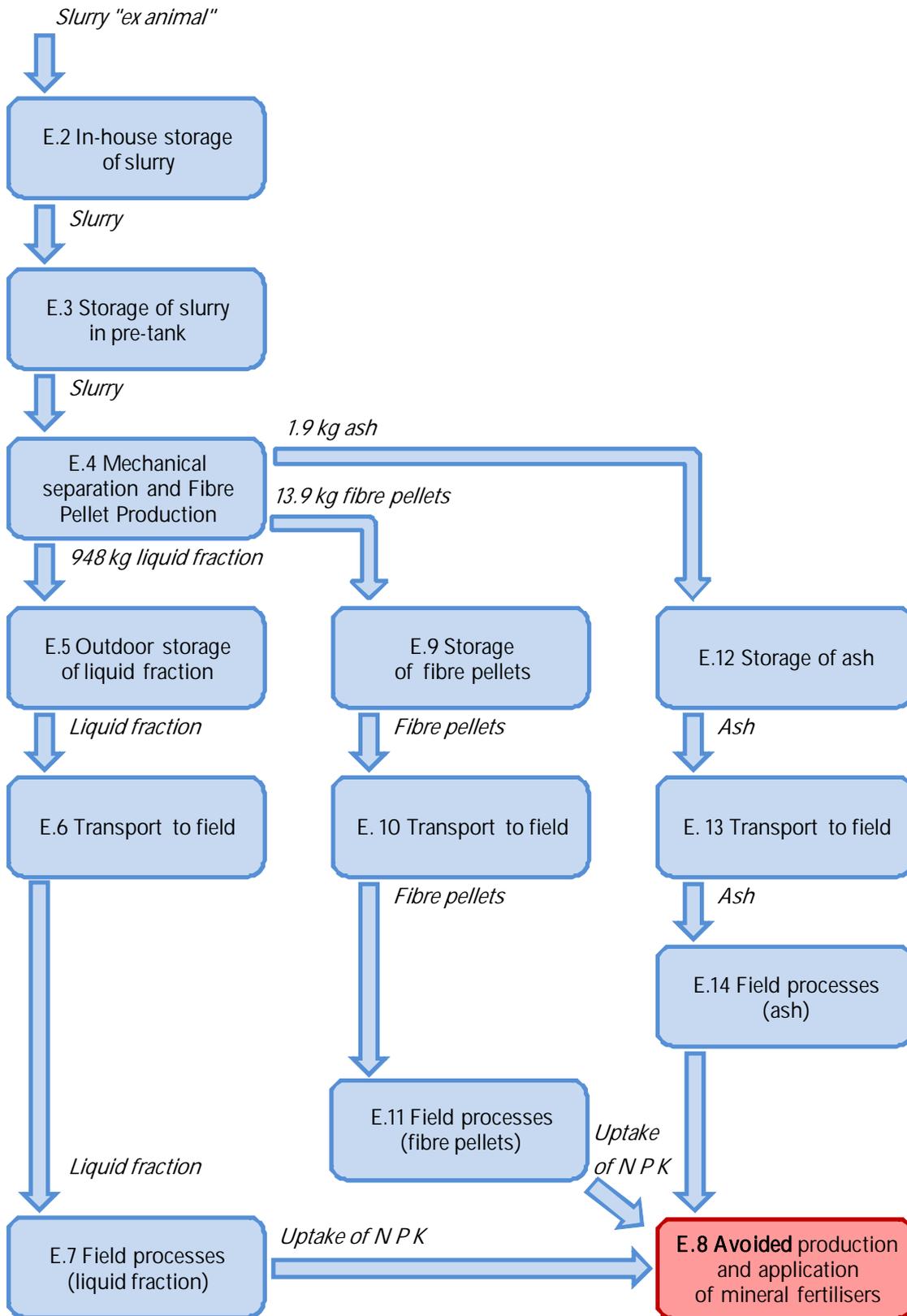
E.1 System description

This appendix contains Life Cycle Inventory data for fibre pellet production in a Samson Bimatech Plant MaNergy 225.

The system in this Annex E is very close to the system in Annex D, however, the fibre pellets are not used for heat production as in Annex D, but for application to the field as fertiliser.

The scenario containing the Energy Plant producing energy based on fibre pellets is shown in figure E.1. The process numbers refer to the heading of the section in this Annex E.

Figure E.1.
Flow diagram for the scenario with production of fibre pellets for fertilising.



E.2 In-house storage of slurry

This process is identical to process C.2 in Annex C.

E.3 Storage of slurry in pre-tank

This process is identical to process C.3 in Annex C.

E.4 Mechanical separation and Fibre pellet production

In the Samson Bimatech Energy Plant, the slurry is separated into a liquid fraction and a fibre fraction, as described in Annex D. The processes for the fibre pellet production in the energy plant are described in Annex D.

When producing fibre pellets as the “primary product” instead of heat, the emissions per 1000 kg slurry is different, as there is less combustion. Approximately 40% of the fibres are used for producing the heat required for drying the fibres. The emissions correspond to approximately 50% of the amount of emissions from when all the fibre pellets are combusted for heat production (Annex D), as the efficiency is slightly lower when the plant is not used to its full capacity.

Accordingly, it is assumed that the emissions are reduced by 50% when producing fibre pellets as the main product and the heat is only for drying the pellets.

The life cycle data for the Fibre pellet production in the Energy Plant are shown in table E.1

As described in Annex D, the mechanical separation separates the slurry into 51.98 kg fibre fraction and 948 kg liquid fraction (“reject”).

From Annex D (table D.1) it can be seen that when 1000 kg of pig slurry undergoing mechanical separation and pellet production, 23.19 kg fibre pellets are produced, based on the mass balances. However, approximately 40% of the fibres are used for producing the heat required for drying the fibres (as described in section E.4 in Annex E). This means that the treatment of 1000 kg pig slurry gives approximately 13.9 kg fibre pellets.

The amount of ash produced is 1.94 kg¹.

¹ 23.19 kg fibre pellets * 40% * 0.209 kg ash per kg DM (See Annex D) = 1.09 kg ash.

Table E.1.

Life cycle data for treatment of slurry in the Samson Bimatech energy. Data per 1000 kg slurry treated.

	Fattening pig slurry	Comments
Input		
Slurry (ex pre-tank)	1000 kg	Slurry directly from the pre-tank under the pig housing units. This is the reference amount of slurry, i.e. the emissions are calculated relative to this.
Output		
Fibre pellets	13.9 kg	In this Annex, all fibre pellets are used for fertilising.
Liquid fraction of the slurry	948 kg	Reject slurry / liquid phase of the slurry
Ash	1.94 kg	
Heat production, surplus.	0 MJ	No surplus heat in this scenario.
Heat production used in the plant	120 MJ	Used in the plant for drying fibres, see 3 lines below the plant
Energy consumption		
Electricity	19 kWh	Personal correspondence with J Mertz, 2008.
Heat	120 MJ	Used in the plant for drying fibres, produced by the plant, see 3 lines above
Wooden pellets	0.078 kg	Wooden pellets are used for heating when starting the plant.
Consumption of materials and chemicals		
Wooden pellets	0.078 kg	For starting the process
Emissions to air		
Carbon dioxide (CO ₂)	18.1 kg	Information from J. Mertz (2009)
Carbon monoxide (CO)	0.0355 kg	Information from J. Mertz (2008)
Methane (CH ₄)	No data	Assumed to be negligible.
Non-methane volatile organic compounds (NMVOC)	No data	
Ammonia (NH ₃ -N)	-	Assumed to be insignificant.
Nitrous oxide (N ₂ O-N)	No data	
Nitrogen oxides (NO _x)	0.05 kg	Information from J. Mertz (2009)
Nitrogen(N ₂)	0.178 kg	Calculated according to mass balances, see text.
Particulates	0.015 kg	Information from J. Mertz (October 2008) Size of the particulates not specified.
Hydrogen sulphide (H ₂ S)	No data	
Sulphur dioxide (SO ₂)	No data	
Odour	No data	
Emissions to water		
No emissions to water		

E.5 Outdoor storage of the liquid fraction

This process is identical to process C.5 in Annex C.

E.6 Transport of the liquid fraction to field

This process is identical to process C.6 in Annex C.

E.7 Field processes (Liquid fraction)

This process is identical to process C.7 in Annex C.

E.8 Avoided production of mineral fertilisers

If using the fibre pellets as fertiliser at fields, the "fertiliser replacement value" needs to be established. As the use of fibre pellets as fertiliser is a "future possibility" for a new technology and as it is not used today, there are no rules for how this is normally handled.

As described in Annex C, the "fertiliser replacement value" of the liquid fraction depends on how the fibre fraction is managed (if it is combusted, sent to a biogas plant or sent to other farms as fertiliser).

The "fertiliser replacement value" is calculated for the total system as follows:

The calculation of the fertiliser replacement value for N is based on Danish Law combined with "common practice". When slurry is separated, the two separated fractions should have the same "fertiliser replacement value" as the non-separated slurry. The "fertiliser replacement value" of the fibre fraction is decided by the producer of the slurry – or in agreement with the receiver of the slurry (and the N content is based on measurements a couple of times a year). In practice, the fertiliser value of the N in the fibre fraction is typically set to 50% (as the receiver is not interested in more N for the N-accounts than necessary) (personal communication with Thorkild Birkmose (2009) and Jens Petersen (2009)).

The N content in the slurry substitutes mineral N-fertiliser, as described in Annex A. The substitution of mineral N-fertiliser is restricted by Danish law (Gødskningsbekendtgørelsen, 2008, and Gødskningsloven, 2006). The farmers have to make accounts on their fertiliser use, and they have to include a fixed amount of the N content of the animal slurry in their fertiliser accounts. The amounts are based on measurements by the farmer. Accordingly, they are assumed to be identical with the calculated values.

First, the "fertiliser replacement value" for the reference system is stated (see Annex A for further details):

- Mineral N fertiliser: 5.00 kg N per 1000 kg slurry ex storage [the value given by the Danish Norm Data, as explained in Annex A] * 1086 kg slurry ex storage per 1000 kg slurry ex animal * 75% [the

replacement value according to (Gødskningsbekendtgørelsen, 2008]
= 4.073 kg mineral N fertiliser

- Mineral P fertiliser: 1.04 kg P per 1000 kg slurry ex storage * 1086 kg slurry ex storage per 1000 kg slurry ex animal = 1.13 kg P
- Mineral K fertiliser: 2.60 kg P per 1000 kg slurry ex storage * 1086 kg slurry ex storage per 1000 kg slurry ex animal = 2.82 kg K

Then, the “N fertiliser replacement value” for the “Fibre Pellets to field – scenario” is calculated:

- The slurry is separated into 51.98 kg fibre fraction and 948.02 kg liquid fraction (see table C.3 in Annex C). As mentioned above, approximately 40% of the fibres are combusted (as fibre pellets) in order to supply the Energy Plant with heat for drying.
- Accordingly, 40% of the liquid fraction is calculated as in Annex D: The amount of N in the liquid fraction of the slurry replace mineral N fertiliser by 85% according to Danish Law (Gødskningsbekendtgørelsen (2008), BEK 789, § 21) when the fibre fraction is combusted: 948.02 kg liquid fraction * 40% [corresponding to the fraction of fibres combusted] * 4.71 kg N per kg liquid fraction after storage [from table C.8 in Annex C] * 1086 kg liquid fraction after storage per 1000 kg liquid fraction before storage * 85% [the mineral fertiliser replacement value when the fibre fraction is combusted] / 1000 kg slurry ex animal = 1.6487 kg mineral N fertiliser
- The theoretical fertiliser value of the fibre fraction that is not combusted (i.e. 60% of the fibre fraction) is calculated as follows: 51.98 kg fibre fraction per 1000 kg slurry ex animal * 7.17 kg N per kg fibre fraction [table C.3 in Annex C] * 60% [fraction that is not combusted] * 50% [the fertiliser value of the fibre fraction is typically 50%, as mentioned above] = 0.1118 kg mineral N fertiliser
- 60% of the liquid fraction is calculated in accordance with the law regarding separation of slurry, as described above. The intention of the law is that for separation of the slurry, the separated fractions should have the same “fertiliser replacement value” as the non-separated slurry. 60% of the “fertiliser replacement value” of the non-separated slurry is 60% of 4.073 kg mineral N fertiliser (see calculations for the reference system above) = 2.4438 kg mineral N fertiliser. Left for the liquid fraction is: 2.4438 kg N – 0.1118 kg N [which is the theoretical fertiliser value of the fibre fraction that is not combusted, as calculated above] = 2.332 kg mineral N fertiliser.
- Accordingly, the “fertiliser replacement value” of the system is:
40% liquid fraction: 1.6487 kg mineral N fertiliser +
Fibre fraction for fertilising the field: 0.1118 kg N +
60% liquid fraction: 2.332 kg mineral N fertiliser
= 4.093 kg mineral N fertiliser for the total system.

This is almost identical to the mineral fertiliser value of the reference system (which is 4.073 kg mineral N fertiliser).

The amount of K and P applied to soil is the same as in the reference scenario, as these are not lost in the system.

The application of fibre pellets to the soil has, however, impact on the crop yield. As the fibre pellets more act as soil structure improvement media than as actual N fertiliser due to the C:N ratio of the fibre pellets (as such a high C

: N ratio will typically give rise to N immobilization as explained in section E.11 below), there will actually be **less** N available for plant growth. It has not been possible to identify the magnitude of a possible reduced crop yield, as the use of fibre pellets has never been tested or tried in real life. However, the amount of fibre pellets applied to field is rather low compared to the liquid fraction in this system (948 kg liquid fraction compared to 13.9 kg fibre pellets) which means that it is likely that the consequences for the overall system will be rather small. The possible consequences are discussed under sensitivity analyses.

E.9 Storage of fibre pellets

This process is identical to the storage of fibre pellets in Annex D.

E.10 Transport to field (fibre pellets)

It is assumed that the transport distance is the same as in the reference scenario in Annex A.

E.11 Field processes (fibre pellets)

The composition of the fibre pellets when they are applied to field is shown in table E.2 below (data from Annex D, table D.1).

Table E.2.
Composition of fibre pellets.

Composition of fibre pellets	
Total mass	1000 kg
Dry matter (DM)	889.3 kg
Total-N	11.6 kg
Total-P	4.31 kg
Potassium (K)	3.58 kg
Carbon (C)	425.2 kg
Copper (Cu)	0.082 kg
Zinc (Zn)	0.242 kg

The field processes are calculated relative to the content of C and N in Annex A, see table E.3.

The emissions of ammonia (NH₃) are calculated by the use of the same emission factor as in Annex A, i.e. 0.138 g NH₃-N per g TAN². Measurements made on “real life” fibre pellets (OK Laboratorium for Jordbrug, 3-2-2009), the NH₄⁺ content of the fibre pellets corresponds to approximately 15.2% of the total N. As can be seen in table E.2, the amount of total-N in the fibre pellets correspond to 11.6 kg N per 1000 kg fibre

² As explained in section “Definitions and abbreviations” in the beginning of the report, TAN and NH₄⁺ is used as synonyms for each other by e.g. Hansen et al. (2008) and Poulsen et al. (2001) in spite of that it is only an approximation. This approximation is also used here.

pellets. Accordingly, the NH_3 emissions can be calculated to 0.243 kg NH_3 per 1000 kg fibre pellets.

The content of C is very high, which gives rise to a large increase in soil C, over 10 years the C content in the soil increases 101.0 (JB3), respectively 106.6 (JB6) kg C per 1000 kg pellets, according to C-TOOL. The majority of the C in the pellets is released as CO_2 though (Table F.9). The above large increase in soil C gives rise to a modeled increase in soil N of 10% of the C increase, 10.1 (JB3) respectively 10.7 (JB6) kg N per 1000 kg pellets. This is only a little less than the N present in the pellets. So, according to this modeling, only 1.5, respectively 0.9 kg N are left for both plant uptake and all N losses, due to the high C : N ratio of the pellets of 39 : 1. Such a high C : N ratio will typically give rise to N immobilization. A C:N ratio of approx. 25 is usually considered the ratio where N mineralisation and immobilisation is in balance (Pierzynski et al., 2005). The present ratio of 39 can thus not be expected to contribute significantly to the N supply, in concordance with the above calculation. It means that the fibre pellets more act as soil structure improvement media than as actual N fertiliser.

After the gaseous losses (Table E.3), there is 0.74 (JB3), respectively -0.21 kg N left for harvest and leaching. The latter small negative value implies that 1000 kg pellets on JB6 will immobilize 0.21 kg N from the soil mineral N content.

These amounts of surplus N are very small, so for simplicity the distribution of the surplus between harvest and leaching for JB3 is assumed to be as for pig slurry (Table A.15). For JB6, the leaching is set to zero. The 100 year leaching values cannot be calculated with the methods used in Annex A, B and C, because of the high C/N ratio. No estimates are therefore given for these values for the fibre pellets.

Table E.3.

Life cycle data for application of slurry and field processes (reference scenario). All data per 1000 kg of slurry ex outdoor storage.

	Annex A Fattening pig slurry	Annex E Fibre pellets	Comments
Input			
Slurry "ex storage"	1000 kg	1000 kg	This is the reference amount, i.e. the emissions are calculated relative to this.
Fibre pellets "ex storage"	Slurry ex storage	Fibre pellets ex storage	
Output			
Slurry on field, fertiliser value	Fertiliser replacement value: See section E.8	Fertiliser replacement value: See section E.8.	See text in section E.8.
Energy consumption			
Diesel for slurry	0.4 litres of diesel	0.4 litres of diesel	Assumed to be the same per kg.
Emissions to air			
Carbon dioxide (CO ₂), JB3	81.6 (99.8) kg	1188.7 (1453.1) kg	Modelled by C-TOOL (Gyldenkærne et al, 2007). 10 year values and 100 year values in parentheses.
JB6	80.2 (99.4) kg	1168.2 (1447.3) kg	
Methane (CH ₄)	Negligible	Negligible	The CH ₄ emission on the field is 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	0.04 kg	NH ₃ emissions during application: 0.5% of NH ₄ ⁺ -N "ex storage", see table A.1 and A.2 and text below. Hansen et al. (2008).
Ammonia (NH ₃ -N) in period after application	0.48 kg	0.243 kg	NH ₃ emissions in the period after application are based on Hansen et al. (2008) and the current slurry distribution in the crop rotation, see text.
Direct emissions of Nitrous oxide (N ₂ O-N)	0.05 kg [0.015-0.15]	0.116 kg	0.01 [0.003 - 0.03] kg N ₂ O-N per kg N "ex storage" for application of animal wastes to soil, based on IPCC (2006, table 11.1).
Indirect emissions of Nitrous oxide (N ₂ O-N)	0.005 kg	0.012 kg	0.01 kg N ₂ O-N per kg (NH ₃ -N + NO _x -N) volatilised (IPCC, 2006, table 11.3). Ammonia emissions given in this table.
Soil JB3	0.014 kg	0.003 kg	Furthermore, nitrate leaching leads to indirect emissions of nitrous oxide.
Soil JB6	0.011 kg	0 kg	
Nitrogen oxides (NO _x -N)	0.005 kg	0.012 kg	NO _x -N = 0.1 * N ₂ O-N according to Nemecek and Kägi (2007)
Nitrogen (N ₂ -N)			See text
Soil JB3:	1.91 (2.12) kg N	0.40 kg	
Soil JB6:	1.50 (1.67) kg N	0.00 kg	
Discharges to soil			
Nitrate leaching			See text
Soil JB3	1.91 (2.12) kg N	0.40 kg	
Soil JB6	1.50 (1.67) kg N	0.00 kg	
Phosphate leaching	0.113 kg P	0.431 kg P	10% of the P applied to field (Hauschild and Potting, 2005 – only 6% of this reach the aquatic environment, see text).
Copper (Cu)	0.0276 kg	0.082 kg	[No data]
Zinc (Zn)	0.0824 kg	0.242 kg	[No data]

E.12 Storage of ash

This process is identical to the storage of ash in Annex D.

E.13 Transport of Ash to Field

This is identical to the transport of ash in Annex D.

E.14 Field processes (ash)

This is identical to the field processes for the ash in Annex D.