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Maersk Drilling and DONG Energy

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Authors:

Maersk Drilling A/S: Lynne Donald
DONG Energy A/S: Signe Sønderby
COWI A/S: Dorte Glensvig Nymann, Christina van Breugel, Anna Juliane Clausen, Jan Boier Pedersen, Linda Høibye, Steffen Brøgger-Jensen, Carsten Jürgensen & Lene Kristensen

Photography:

Maersk Drilling A/S & DONG Energy A/S

Illustration:

COWI A/S

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Preface

This project is a joint effort between Maersk Drilling (MD), DONG Energy (DONG) and COWI on demonstrating the benefits of using natural capital accounting (NCA) data on a specific business activity.

The objective of this development project is to develop and pilot test a NCA approach covering the construction of the off shore Hejre HA-1 production well using data from start-up to completion and focusing on societal costs from environmental impacts on air and water.

The well is part of the Maersk Drilling (MD) and DONG Energy (DONG) joint operation at the Hejre Field in the North Sea, where Maersk Resolve mobile offshore drilling unit is under long-term contract. Establishing the Hejre HA-1 well is a 'High Pressure High Temperature' drilling operation (HPHT).

The project is supported by the Danish Environmental Protection Agency as well as the mentioned 3 companies.

Resume & konklusion

Dette udviklingsprojekt er designet for at demonstrere den forretningsmæssige værdi ved anvendelse af Natural Capital Accounting (NCA) i forbindelse med operationel og strategisk beslutningstagning i virksomheder. Pilotprojektet omfatter udarbejdelsen/opgørelsen af en NCA dækkende etableringen af en olie- og gasbrønd i Nordsøen.

Natural Capital Accounting tilgangen bruges til at sætte pris i kroner og øre på de miljøpåvirkninger, som aktiviteter i hele virksomheders værdikæde påfører samfundet.

Dette udviklingsprojekt har anvendt en lidt anderledes tilgang end den, der er anvendt af bl.a. NOVO Nordisk, Kering og Puma i deres Environmental Profit & Loss Accounts (EP&Ls), som er en NCA tilgang. Frem for at levere en NCA, der dækker alle miljømæssige omkostninger for samfundet, men kun i dele af værdikæden, har udviklingsprojektet i højere grad fokuseret på at dække miljøpåvirkninger i hele værdikæden for udvalgte materialer, som anvendes ved etableringen af boringen. Ligeledes har fokus været at sikre transparente metoder og genanvendelige sted- og virksomheds-specifikke data, som også er relevante ift. forretningsmæssige beslutninger. Ydermere er udviklingsprojektet designet sådan, at det på et senere tidspunkt kan udvides med flere typer af emissioner og påvirkninger, andre materialer og teknologier samt flere typer af aktiviteter, f.eks. produktion af olie, administrationer på land mm.

Formål

Formålet med dette udviklingsprojekt er,

- At udvikle og pilotteste en NCA tilgang, som dækker etableringen af offshore olie- og gasbrønden Hejre HA-1. Der anvendes data fra opstart til færdiggørelse af brønden samt fokuseres på samfundsmæssige omkostninger, som følge af miljøpåvirkninger i hele værdikæden ved at se på luftemissioner og udledninger til vandmiljøet.
- At udvikle et værktøj, som gør det muligt at vurdere de miljømæssige omkostninger ved forskellige designs af brønden, dvs. forskellig længde af sektioner, forskellige teknologier til behandling af slop vand, variabel mængde flare gas samt variabel antal utilsigtet udledning af mindre mængder af diesel og udvalgte typer af kemikalier

Etablering af boringen HA-1 er en del af Maersk Drilling (MD) og DONG Energy (DONG)'s samarbejde omkring Hejre Feltet i Nordsøen. Det er MD's mobile offshore borerig Resolve, som udfører borearbejdet og færdiggørelsen af HA-1 brønden. Brønden er en High Pressure High Temperature proces.

Udviklingsprojektet omfatter følgende hovedaktiviteter:

- **Afgrænsning af projektets fokus**, herunder specificering af input materialer, typer af emissioner og påvirkninger samt hvilke led i værdikæden, som skal inkluderes i projektet. Ligeledes afklaring af forudsætninger og antagelser, som danner grundlag for dataindsamling, værdisætningsmetode, beregninger samt følsomhedsanalyser.
- **Indsamling og systematisering** af de bedst mulige fysiske emissionsdata i en **database** samt værdisætningsestimater, der oversætter emissioner til miljøomkostninger for samfundet.

- Udvikling af et **beregningsværktøj**, som sammenstiller de fysiske data og oversætter dem til monetære værdier for dermed at muliggøre sammenligning på tværs af typer af emissioner, materialer, dele af værdikæden mm.
- Gennemføre **følsomhedsanalyser** af resultaterne for at vurdere, robustheden af konklusionerne.
- Udvikling af et **brugerflade værktøj**, der muliggør afprøvning af forskellige designs af brønden, forskellige valg af teknologier til behandling af slop vand samt betydningen af utilsigtet udledning af mindre mængder diesel eller kemikalier og endelig at bruge resultaterne til at vurdere NCA resultaternes anvendelighed ift. at understøtte operationelle og strategiske beslutningsprocesser i virksomheden.
- **Rapportering**, herunder diskussion af resultater samt konklusion.

Afgrænsning af opgaven
Udviklingsprojektet er afgrænset til at omfatte luftemissioner og udledninger til vandmiljøet. Disse miljøpåvirkninger er relateret til installeringen af stålrør i boringen under borearbejdet og ved færdiggørelse af brønden, anvendelsen af fossile brændsler på boreriggen, forsyningsskibe, andre fartøjer og helikoptere, samt kemikalier anvendt ved boring af brønden. Med afsæt i disse anvendte materialer medtages emissioner til luft og udledninger til vandmiljøet i den opstrøms del af værdikæden. Endelig omfatter udviklingsprojektet de nedstrøms emissioner til luft og udledninger til vandmiljøet. Dette inkluderer de tilladte udledninger til havet under borearbejdet, samt udledninger til vandmiljøet som følge af on-shore behandling af opboret materiale samt slop vand, begge med rester af boremudder og kemikalier anvendt ved etableringen af boringen.

Endelig modelleres de miljømæssige omkostninger forbundet med utilsigtede udledninger af mindre mængder af diesel og kemikalietyper til havet. Dette har til formål at synliggøre den relative betydning af de miljømæssige påvirkninger og omkostninger for samfundet ved utilsigtet udledning til havet sammenlignet med de øvrige miljømæssige omkostninger. På tilsvarende vis undersøges de miljømæssige omkostninger forbundet med flaring.

Følgende parametre bruges til at beskrive emissioner til luften i hele værdikæden:

- Drivhusgasser (GHG, omfattende CO_2, N_2O and CH_4), opgjort som CO_2 ækvivalenter
- SO_X (SO and SO_2) opgjort som SO_x
- NO_X (NO and NO_2) opgjort som NO_x
- Partikler, PM som $PM_{2.5}$

I Tabel A fremgår hvilke aktiviteter, som er fravalgt i udviklingsprojektet.

TABEL A: EKSEMPLER PÅ HVAD DER IKKE ER INKLUDERET I UDVIKLINGSPROJEKTET. BEMÆRK VENLIGST, AT LISTEN IKKE ER UDTØMMENDE.

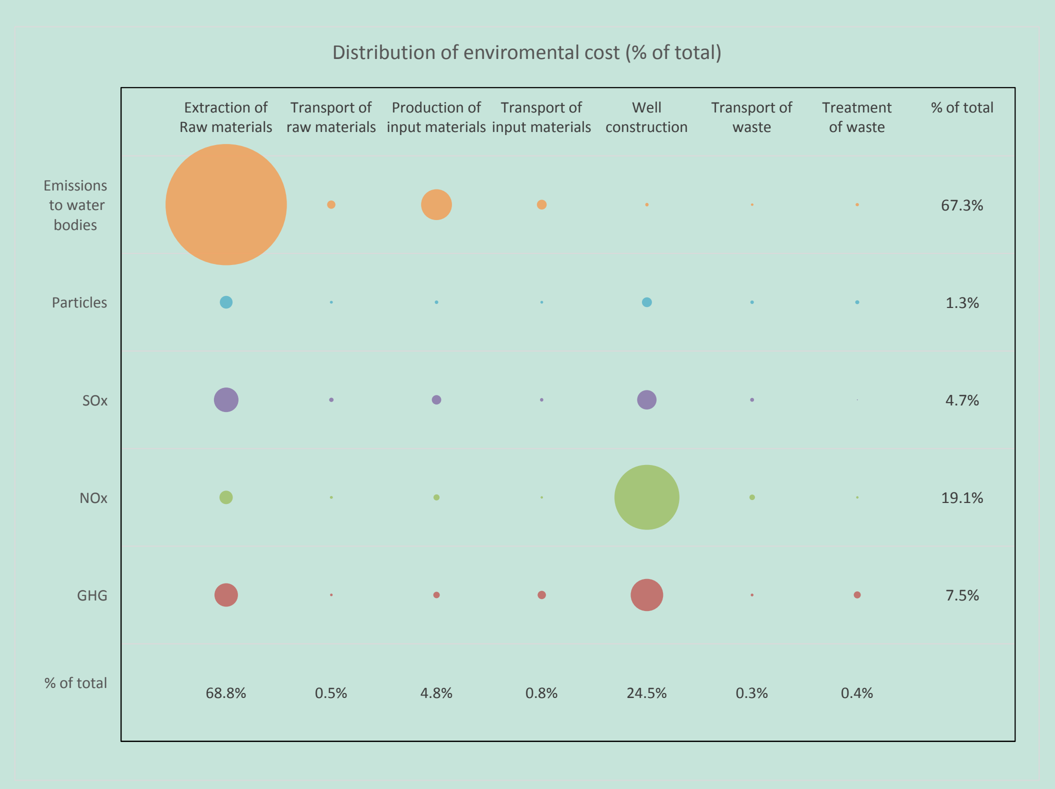
- Design, produktion, transport og dekommisionering af både borerig, produktionsplatform, fartøjer, helikoptere og andet udstyr
- Design, produktion, drift og vedligehold samt dekommisionering af aktiviteter og udstyr på land som supporterer riggen, f.eks. kontorer, lager, leverandører mm
- Test af HA-1 brønden og produktion af olie fra brønden. Flaring som følge af testen er adresseret som et Tanke Eksperiment
- Aktiviteter og miljøpåvirkninger heraf i havbunden.
- Anden udledning til havet end procesvand fra slop unit
- Utilsigtet spild af råolie, f.eks. fra blow-out
- Black carbon i luft emissioner
- Marin akustisk forurening
- Miljøpåvirkninger som følge af anvendelse af land generelt i hele værdikæden, inkl. Deponier
- Stand-by fartøjer og sikkerhedsudstyr
- Andre typer af affald end materiale opboret fra brønden (mud & cuttings) og slop vand
- Påvirkninger af human kapital og/eller social kapital
- Påvirkninger som følge af at de anvendte materialer og ressourcer ikke er til rådighed for anden alternativ anvendelse. F.eks. at forbrugt vand eller olie ikke kan anvendes til andre formål, som kunne have anden samfundsmæssig værdi.

Resultater

Figurerne A, B og C herunder viser hovedresultaterne af NCA'en. Resultaterne omfatter det faktiske setup anvendt ved etableringen af brønden. Til de beregnede miljømæssige omkostninger igennem hele værdikæden er anvendt værdisætningsestimater i forhold til typen af emissioner, deres type af påvirkning samt den geografiske placering.
Forkortelser anvendt i figurerne fremgår af Tabel B herunder.

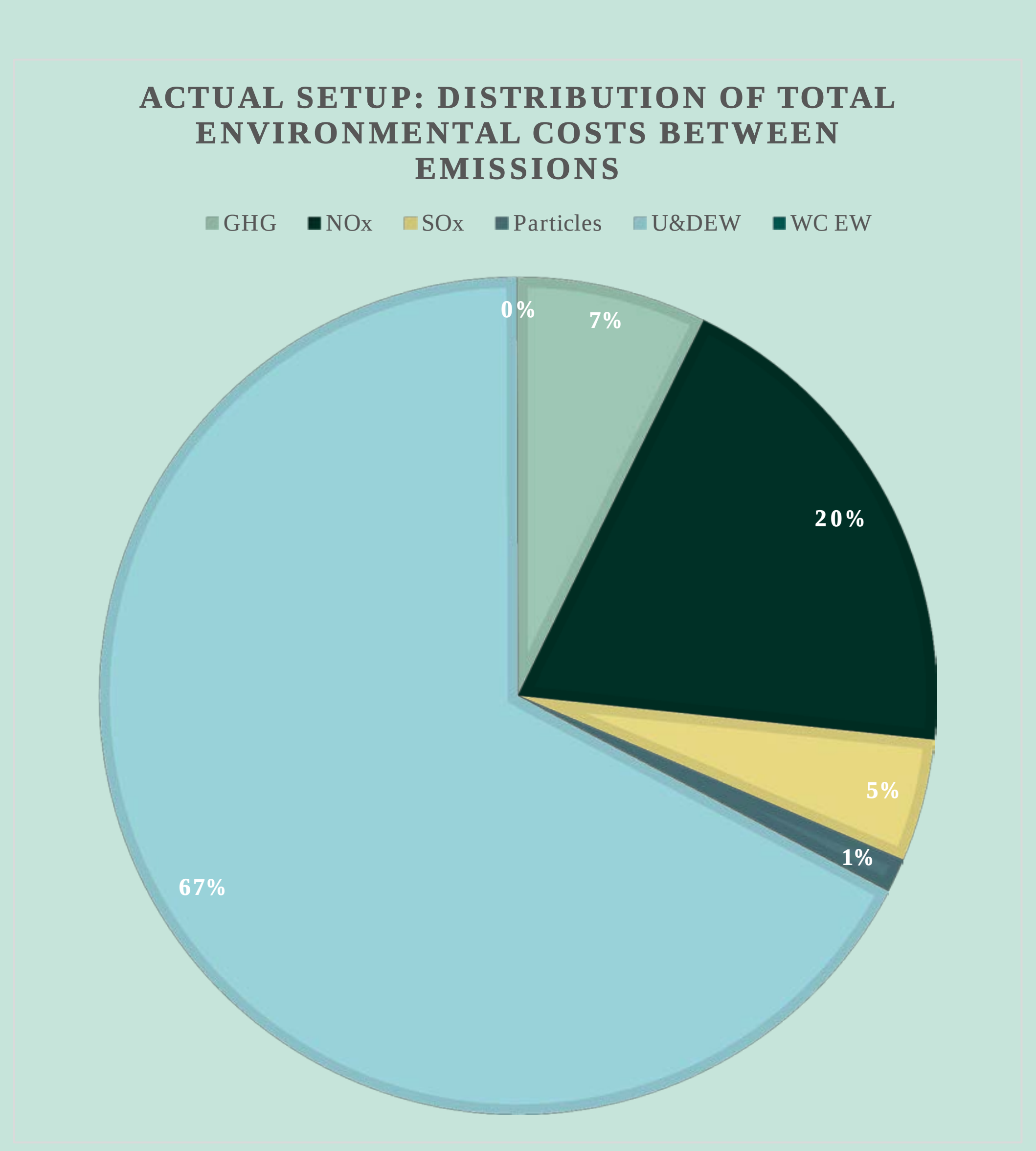
TABEL B: FØLGENDE FORKORTELSER ER ANVENDT I ILLUSTRATIONERNE

- Led i værdikæden (Tiers): Opstrøms (eng.: Upstream (U)), Etablering af boring (eng.: Well Construction (WC)) og nedstrøms (eng.: Downstream (D)). Med 'Raw materials' forstås 'Extraction of raw materials', dvs. udvindelse og bearbejdning af råmaterialer'
- Påvirkninger som følge af forskellige typer af emissioner og udledninger til vandmiljøet i kombination med led i værdikæden (F.eks. U&DEW, op- og nedstrøms udledninger til vandmiljøet):
    - Påvirkninger som følge af udledning til vandmiljøet (eng.: Emissions/discharges to water bodies (EW))
    - Påvirkning som følge af emission af drivhusgasser til luft (GHG)
    - Påvirkning som følge af emission af NO_X til luft (NO_X)
    - Påvirkning som følge af emission af SO_X til luft (SO_X)
    - Påvirkninger som følge af emission af partikler til luft ($PM_{2.5}$)

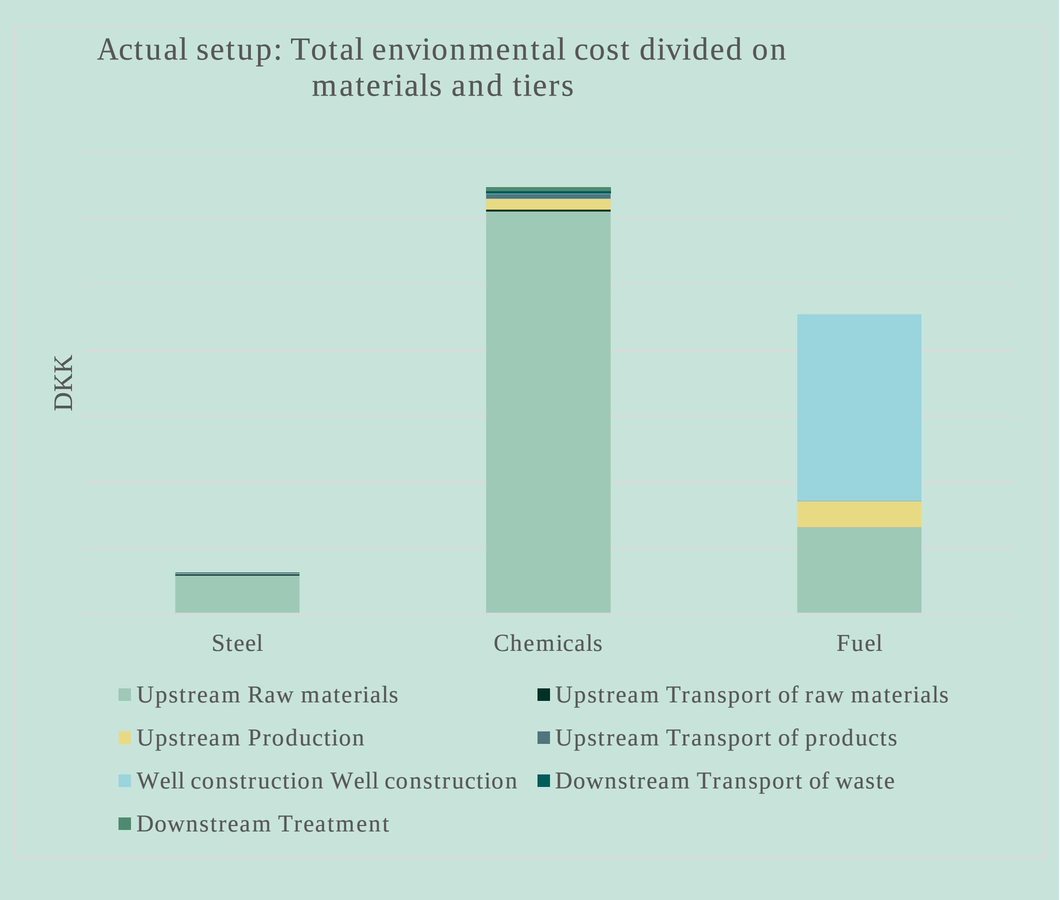


FIGUR A: DE TOTALE MILJØMÆSSIGE OMKOSTNINGER SOM FØLGE AF ETABLERINGEN AF BORING HA-1, FORDELT PÅ LED I VÆRDIKÆDEN. L

I figur A er fremgår de samlede miljømæssige omkostninger som følge af etableringen af boring HA-1, fordelt på led i værdikæden. Omkostningerne er yderligere fordelt på typer af emissioner. For opstrøms udledninger til vandmiljøet er det antaget, at udledninger til vandmiljøet fra råvareproduktion og produktion af kemikalier og stål udgør 50% af vandforbruget. For produktion af brændsler er det antaget at udledningen udgør 100 % af vandforbruget. Bemærk at 'Well construction' inkluderer emissioner, som følge af transport af materiale og personale med fartøjer og helikoptere. Emissioner som følge af produktion og transport af brændstof til Esbjerg havn – dvs. det brændstof som anvendes på riggen og i fartøjer og helikoptere - er medregnet under de opstrøms led. Tilsvarende gælder for andre input materialer til riggen og nedstrøms brug af brændstof og el.



FIGUR B: DEN SAMLEDE MILJØMÆSSIGE OMKOSTNING FORDELING PÅ TYPER AF EMISSIONER/UDLEDNINGER



FIGUR C: DE SAMLEDE MILJØMÆSSIGE OMKOSTNINGER FORDELT PÅ TYPER AF MATERIALER OG LED I VÆRDIKÆDEN.

Resultaterne viser, at:

- Langt størstedelen af de samlede miljømæssige omkostninger i værdikæden skyldes påvirkninger af vandmiljøet i de opstrøms led af værdikæden, her særligt produktion af råvarer som indgår i de materialer, der anvendes på boreriggen. Den næststørste andel af miljøomkostningerne vedrører emission af NO_x og GHG, se også Figur A
- De miljømæssige omkostninger relateret til opstrøms produktion af råvarer brugt til produktion af stål og kemikalie produkter, der anvendes på boreriggen, udgør henved 2/3-dele af de samlede miljøomkostninger. Emissioner under selve boreaktiviteten og etableringen af brønden udgør kun ca. ¼ del af de samlede miljøomkostninger, se Figur B.
- Af Figur C fremgår det, at de miljømæssige omkostninger forbundet med fremstillingen af kemikalier udgør langt den største andel af den samlede miljøomkostning i værdikæden. Også miljøomkostningerne forbundet med fremstillingen af brændstof er betydelig, mens miljøomkostningerne forbundet med fremstillingen af stålrør til brønden kun udgør en lille del af det samlede monetære fodaftryk.
- Langt størstedelen af de miljømæssige omkostninger forbundet med selve borearbejdet vedrører afbrænding af brændsel, se Figur A og B.
- De miljømæssige omkostninger forbundet med den tilladte udledning af kemikalier til havet under selve borearbejdet udgør en ubetydelig andel sammenlignet med de øvrige påvirkninger, se Figur A og B.

De miljømæssige omkostninger pr. meter boring er udregnet for at teste betydningen af forskellige design af boringen og for at teste om NCA data kan anvendes i operationelle og strategiske beslutningsprocesser. Meter-prisen er stærkt afhængig af bl.a. diameter af boringen, anvendelsen af kemikalier og oppe-tiden (dvs. hvor stor andel af tiden der bores). Der er beregnet miljøomkostninger for en række forskellige design af brønden, idet sektionslængder med given diameter blev varieret, mens den samlede længde af boringen blev holdt konstant. Resultatet af beregningerne viser, at der næsten ingen variation er i de samlede miljøomkostninger. Dette skyldes, at langt størstedelen af de miljømæssige omkostninger ligger i opstrøms dele af værdikæden og at ændringer i design samlet set har mindre betydning end længden af boringen, samt at der kun er en af sektionerne, som afviger væsentligt i pris per meter.

Som tanke eksperimenter er de miljømæssige omkostninger beregnet for *fiktive* utilsigtede udledninger af mindre mængder af diesel og typer af kemikalier. Bemærk, at data som er anvendt til disse tanke-eksperimenter ikke stammer fra faktiske udledninger fra Hejre Feltet, men antages repræsentative for en potentiel utilsigtet udledning til havet.

For utilsigtede udledninger til havet er miljøpåvirkninger vurderet ud fra beregning af de påvirkede marine arealer, idet en PEC/PNEC fortyndingsmodel er anvendt. Metoden tager ydermere hensyn til de kemiske egenskaber af den udledte substans, ligesom fysiske og biologiske processer er adresseret. Både en rummelig og en tidsmæssig reduktionsfaktor blev indarbejdet for at vurdere *størrelsesordenen* af miljømæssige omkostninger. Vurderingen viser, at der er mange parametre i spil ift. hvor store miljøpåvirkninger og –omkostninger, som følger af de utilsigtede udledninger. Vurderingen viser også, at udledninger af diesel er mere problematiske end en tilsvarende udledning af kemikalier ift. påvirket havareal. De specifikke resultater skal ses som indikation på størrelsesordenen af miljøomkostninger forbundet med utilsigtede udledninger. Tanke Eksperimenterne demonstrerer, at den udviklede tilgang med anvendelsen af lokal viden om fysiske, kemiske og biologiske forhold samt værdisætnings estimater er en farbar vej ift. at vurdere miljømæssige omkostninger forbundet med utilsigtede udledninger til havs.

Flaring af gas under test af brønden blev også adresseret som et Tanke-eksperiment, idet HA-1 brønden ikke er blevet testet. De beregnede miljømæssige omkostninger forbundet med flaring viser, at flaring under test af brønden vil udgøre mindre end 1% af de samlede miljømæssige omkostninger.

Følsomhedsanalyse

Størstedelen af data anvendt i beregningerne er moniteringsdata fra boreriggen leveret af enten MD eller DONG. Sekundært stammer data fra årlige miljørapporter fra leverandører af serviceydelser eller specifikationer fra aktuelle teknologier anvendt. Resterende data er fremskaffet via LCA'er. Der er således ikke anvendt data fra EEIO tabeller (Environmental Extended Input Output). Et sæt af værdisætningsestimater, der relaterer sig til miljøpåvirkninger i givne dele af værdikæden, blev identificeret sammen med yderligere 3 sæt af estimater (lav, høj og Trucost m.fl.), som anvendes til at følsomhedsvurdere resultaterne. Følsomhedsanalyserne førte ikke til resultater, der ændrer de præsenterede konklusioner i denne rapport.

NCA datas anvendelighed ift. operationelle og strategiske beslutningsprocesser

De miljømæssige omkostninger relateret til installation af RENA Slop Water Treatment Unit på boreriggen blev vurderet som et alternativt til den konventionelle behandling af slop vand, dvs. transport til og behandling på land. Beregningerne viser, at installationen af RENA unit'en medførte en betydelig reduktion i miljøomkostningerne relateret til behandling af slop vand, også når alle omkostninger i værdikæden blev medtaget.

Resultaterne viser, at NCA data svarende til data udviklet i dette projekt skaber værdi for både operationelle og strategiske beslutningsprocesser i virksomhederne og at data kan anvendes på mange måder:

- NCA data er meget anvendelige til sammenligning af forskellige teknologier, idet NCA data tilfører nye aspekter til beslutningsgrundlaget og udemærker sig ved at have samme enhed (kroner) som f.eks. anskaffelsesomkostninger, driftsomkostninger mm.
- Den høje andel af de miljømæssige omkostninger i opstrøms led af værdikæden er også set ved andre NCA analyser. Dette peger på en generel tendens til, at størstedelen af de miljømæssige omkostninger relaterer sig til primær produktionen af råvarer og materialer. Det peger også på, at der er behov for en ændring af fokus hos hhv. virksomheder og myndigheder ift. målet om at sætte ind der, hvor der opnås størst miljømæssig gevinst af de investerede ressourcer. Endelig peger resultaterne på, at der kan opnås gevinster ved at øge genanvendelsen af materialer f.eks. via anvendelse af cirkulære forretningsmodeller, og der er behov for at skabe øget opmærksomhed på de mulige gevinster, der ligger i at medtænke opstrøms fodaftryk i bl.a. design og indkøbsstrategier.
- Fordelingen af miljømæssige omkostninger generelt og specifikt ift. den høje andel af omkostninger forbundet med opstrøms aktiviteter åbner op for en ændring i dialogen med interessenter, herunder mellem myndigheder og med leverandører. Et nøglespørgsmål er her, hvor og hvordan kan vi reducere det samlede fodaftryk mest omkostningseffektivt?
- NCA data kan også anvendes af materiale- og teknologileverandører og serviceleverandører i salgs- og branding sammenhænge, idet NCA data kan anvendes til at differentiere sig fra øvrige leverandører. Set fra kundens synspunkt kan efterlysning af NCA data fra leverandører medvirke til, at en større del af værdikædens aktører bliver inddraget som aktive medspillere i transitionen mod mere miljøvenlige materialer og løsninger og mere transparent dokumentation.
- Projektet viser, at inddragelse af NCA data i beslutningsgrundlag medvirker til at kvalificere og kvantificere diskussionen om design, investeringer, drift og strategi.
- NCA data tilfører nye vinkler på miljørapporteringen og miljøledelse generelt: Viden om de miljømæssige omkostninger i forskellige dele af værdikæden åbner op for et større mulighedsrum ift. kontinuerlige forbedringer, dokumentation af bæredygtighed og rapportering på samfundsansvar.

Samlet set har udviklingsprojektet demonstreret, at NCA data giver forretningsmæssige værdi til operationelle og strategiske beslutningsprocesser.

Summary & conclusion

This pilot project is designed to demonstrate the business value from using Natural Capital Accounting (NCA) in operational and strategic decision making in businesses. The pilot project comprises natural capital accounting for the construction of an oil & gas well in the North Sea.

The Natural Capital Accounting approach entails estimating the societal costs and gains due to environmental impact in monetary terms from activities in part of or the full value chain.

The pilot project has chosen a somewhat different NCA approach in comparison with the Environmental Profit & Loss Accounts (EP&L's) published by e.g. NOVO Nordisk; Kering and PUMA. The focus is more on providing transparent methodologies and data for making the NCA site-specific, reusable and relevant to business decision making rather than providing a full cost estimate of all environmental cost to society. The pilot project is designed in a way that allows for later expansion of types of impacts, input materials, technologies and other activity types e.g. well service, administration onshore.

Objective
The objective of this development project is:

- to develop and pilot test a NCA approach covering the construction of the offshore Hejre HA-1 production well using data from start-up to completion and focusing on societal costs in the full value chain from environmental impacts on air and water.
- to develop a tool allowing users to assess the environmental costs using an alternative set-up of the well, for example different drill section sizes and choice of wastewater treatment technology, level of flaring during testing and frequencyof unplanned discharge of small amounts of diesel oil and non-toxic chemicals

The well is part of the Maersk Drilling (MD) and DONG Energy (DONG) joint operation in the Hejre Field in the North Sea, where the Maersk Resolve mobile offshore drilling unit is under long-term contract. Construction of the Hejre HA-1 well is a 'High Pressure High Temperature' drilling operation (HPHT).

The project includes the following major activities:

- **Scoping** of the pilot project including deciding types of input materials, types of emissions and tiers in the value chain to be included as well as the assumptions associated with both inventory and valuation methodology
- **Collecting and systemising** the best possible physical emission data in a **database** including monetary valuation estimates.
- Developing a **calculation tool** summing up the physical data and translating them into monetary values allowing comparison across footprints and different parts of the value chain as an **overview** of the results
- Performing **sensitivity testing** of results to determine the robustness of conclusions
- Developing an **interface tool** to test the effect of different layouts of the well construction, choices of technologies and importance of unintended discharges of

small amounts of diesel and non-toxic chemicals, and perform usability test of NCA data in operational and strategic decision making in the businesses
- **Reporting**, including discussion and conclusion

The pilot project focuses on providing transparent methodologies and data for making the NCA site-specific and relevant to operational and strategic business decision making rather than providing a full cost estimate of all environmental cost to society.

Scope

The pilot project scope includes emissions to air and water from installing steel piping during well construction, fossil fuel combustion for powering the rig, vessels, supply boats and helicopter and chemicals for drilling. Furthermore the pilot project includes upstream emissions to water and air following the production and transport of the imported materials mentioned. Downstream impacts to water and air include impacts from permitted discharges of drill cuttings, mud and slop water to sea and drill cuttings, mud and slop water returned to shore for treatment. For demonstrative purposes the environmental impacts and cost associated with different technologies for handling slop water are addressed. The following parameters for emissions to air are covered both upstream, in construction of well (including fuel consumption for vessels, rig and helicopters - the latter transporting personnel and supplies from Esbjerg Harbour to the rig) and downstream:

- Green House Gas (GHG, consisting of CO_2, N_2O and CH_4), estimated as CO_2 equivalents
- SO_X (SO and SO_2) estimated as SO_x
- NO_X (NO and NO_2) estimated as NO_x
- Particulate matter, PM as $PM_{2.5}$

Furthermore fictitious scenarios of unintended discharge of chemicals or diesel oil as well as flaring during testing of the well are included as ‘Thought Experiments’ (i.e. to demonstrate the approach and theories used in this project by applying them to hypothetical scenarios) In Table A, examples of activities that has been scoped out of the pilot project are presented.

TABLE A: EXAMPLES OF WHAT IS NOT INCLUDED IN THE PILOT PROJECT SCOPE. PLEASE NOTE, THAT THE LIST NOT FULLY EXHAUSTIVE, PLEASE REFER TO THE TEXT FOR INFORMATION OF WHAT IS INCLUDED IN SCOPE

- Design, production, transport and decommissioning of both drilling rig, production platform, vessels, helicopters and other transport or operational agents
- Design, production, operation, maintenance and decommissioning of onshore activities supporting activities on the rig, e.g. offices, storage facilities, supply of materials not included in scope
- Testing of the HA-1 well and production of oil from the HA-1 well. Flaring following testing of the well is addressed as an thought experiment, allowing a choice of flaring volume
- Subsea operations and subsea impacts
- Discharge of water from the rig, except from the slop unit
- Unintended spills of crude oil from e.g. blow-out
- Black carbon in air emissions
- Marine acoustic pollution
- Land use impacts in general in full value chain, including e.g. landfilling of treated drill cuttings
- Stand-by boats and equipment including emergency drills etc.
- All types of waste except drilling waste (mud and cuttings) and slop water
- Impacts on human capital are generally not included in scope
- The impact that the used of resource will have as they cannot be used alternatively. In other words if a non-renewable resource is used for the purpose of this project it cannot be used for other purposes. The difference in the value that the resource represents based on the usage is not included in the scope due to the lack of knowledge of alternative uses at the location but also the general lack of societal assessment of non-renewable resources. This will also be the case for renewable resources like water but the value will be lower.

Overall results

In the illustrations figures A, B and C below, the central results are presented for the actual set-up of the well. Environmental costs are calculated using valuation estimates representing the type of emission, the types of impacts and the location of the impacts.

The terminology and abbreviations are presented in table B.

TABLE B: THE FOLLOWING ABBREVIATIONS ARE USED IN THE ILLUSTRATIONS

- Tiers: Upstream (U), Well Construction (WC, including transport of materials and personnel by vessel or helicopter between Esbjerg Harbour and the rig) and Downstream (D). The activity ‘Raw materials’ in upstream tier is understood as ‘Extraction of raw materials’.
- Impacts from different types of emissions to air or emissions/discharges water e.g. in combination with the tier (e.g. U&DEW, up- & downstream emissions to water):
    - Emissions/discharge to water bodies (EW)
    - Impacts from emissions of greenhouse gasses to air (GHG)
    - Impacts from emissions of NO_X to air (NO_X)
    - Impacts from emissions of SO_X to air (SO_X)
- Impacts from emission of particles to air ($PM_{2.5}$)

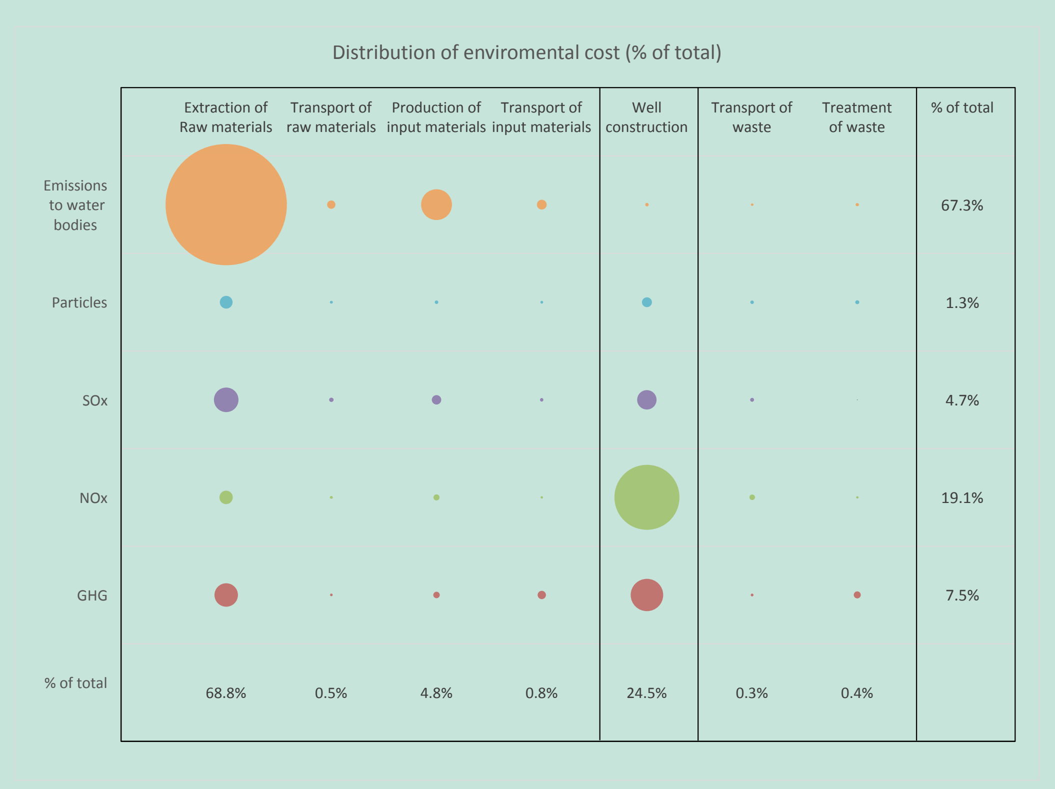


FIGURE A: DISTRIBUTION OF THE TOTAL ENVIRONMENTAL COSTS IN THE VALUE CHAIN DIVIDED BY TYPES OF EMISSIONS. UPSTREAM EMISSIONS TO WATER BODIES ASSUME THAT WATER DISCHARGE EQUALS 50% OF THE WATER USAGE FOR STEEL AND CHEMICAL PRODUCTION AND 100% FOR FUEL PRODUCTION. PLEASE NOTE THAT TIER 'WELL CONSTRUCTION' INCLUDES EMISSIONS FROM OPERATION OF RIG AND OPERATION OF VESSELS AND HELICOPTERS FOR TRANSPORT OF MATERIALS AND PERSONNEL. EMISSIONS FROM PRODUCTION AND TRANSPORT OF FUELS TO ESBJERG HABOUR FOR OPERATING THE VESSELS, RIG AND HELICOPTERS ARE INCLUDED IN 'UPSTREAM' TIERS. A SIMILAR APPROACH APPLIES FOR OTHER INPUT MATERIALS BOTH IN WELL CONSTRUCTION AND IN DOWNSTREAM ACTIVITIES.

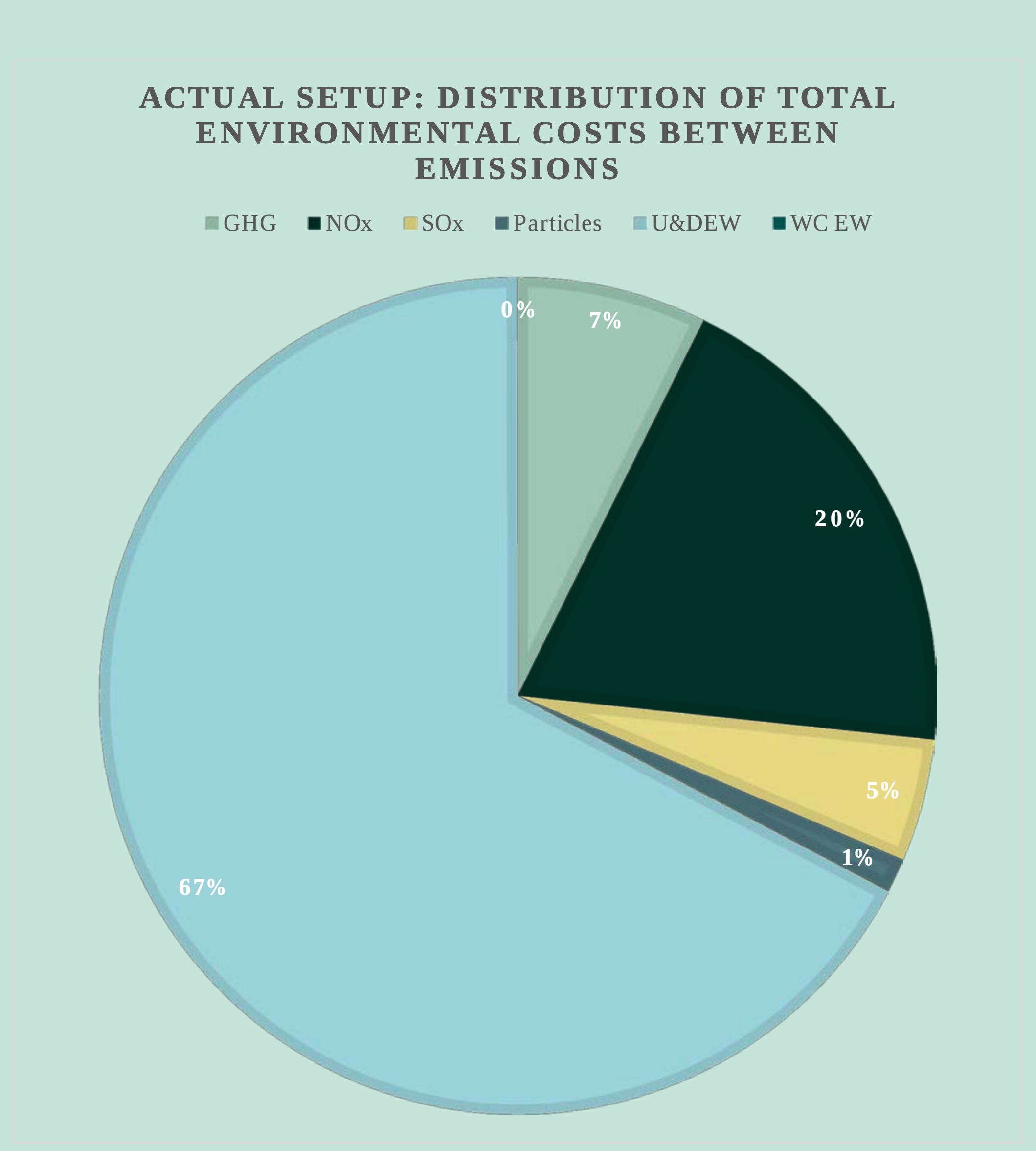


FIGURE B: DISTRIBUTION OF THE TOTAL ENVIRONMENTAL COST IN THE VALUE CHAIN DIVIDED ON EMISSIONS TYPES.

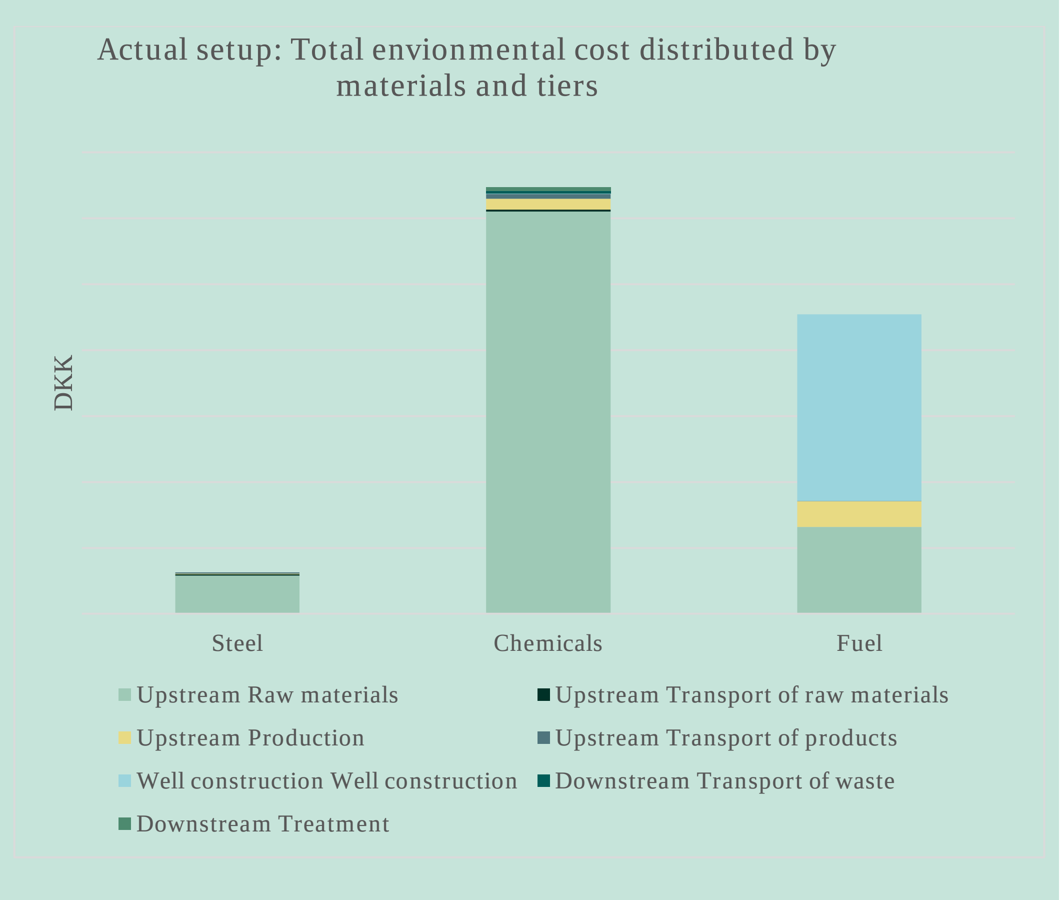


FIGURE C: DIVISION OF TOTAL ENVIRONMENTAL COST IN THE VALUE CHAIN DISTRIBUTED BY TYPES OF MATERIAL AND TIERS

The overall NCA results show that:

- The majority of the total environmental cost in the value chain is associated with impacts on water bodies due to usage and discharge of water in the upstream parts of the value chain (i.e. water usage and discharge in activities outside the actual construction of the well). This is followed by emissions of NO_X and emission of greenhouse gases (GHG). Please refer to Figure A.

- The environmental costs related to upstream production of raw materials used for steel, chemicals and fuels are responsible for two thirds of the total environmental cost in the value chain, followed by the cost of emissions during well construction accounting for approximately one quarter of the total cost, see Figure B.

- When looking at the distribution of total environmental cost between the input materials: steel, chemicals and fuels - it is seen that environmental costs associated with chemicals are responsible for the majority of the total environmental costs in the value chain, see Figure C. The results also show that the raw materials used for production of chemicals are responsible for a substantial part of the total environmental cost in the value chain. Environmental costs related to fuels are also significant whereas steel only has minor importance compared with the other input materials.

- The majority of the environmental cost in the well construction tier is associated with combustion of fuels, see Figure A & B.

- Environmental cost associated with permitted discharge of chemicals to sea during well construction is insignificant compared to the other types of impacts, see Figure A & B.

The environmental cost pr. meter drilled was calculated in order to test the effect of different well designs and to test the usability of the NCA data in operational and strategic decision making. The meter-costs are highly dependent on, among others aspects, the drill diameter, the usage of chemicals and the downtime (periods when not drilling). Test of different designs of the well in terms of length of sections, while keeping the total length of the well shows almost no variance in the total environmental cost. This is due to the fact that the majority of the environmental costs relate to upstream activities and changes in design are minor as the total length is constant.

As a though experiment, the environmental costs related to a hypothetical unintended discharge of small amounts of black, red or yellow chemicals or diesel oil were addressed. Please note that the data used for estimating the environmental cost relating to unintended discharges is not from Hejre Field but an assumed representative value for a potential unintended discharge.

For unintended discharges the impacts were quantified through calculations of the affected marine area (using a PEC/PNEC dilution model) taking into account, among others aspects, the chemical characteristics of the spilled medium as well as physical and biological processes. The assessment shows that there are many parameters in play on how a spill behaves at sea. The assessment shows that diesel oil spills are more problematic than chemical spills in terms of affected area. Both a spatial and a temporal reduction factor were used to estimate a *scale* of potential environmental cost associated with an unintended discharge of diesel oil. The specific results should be taken as an indication of the magnitude of environmental cost related to spills. Furthermore, the thought experiment on unintended discharges demonstrates that the calculation approach combined with reliable and specific local knowledge on the physical, chemical and biological context as well as offshore valuation estimates may be a viable methodology.

Flaring during testing was also included as a hypothetical thought experiments, using flaring experiences from other rigs. The calculated environmental cost associated with a potential flaring during the well testing accounts for less than 1% of the total environmental cost in the value chain for the construction of the well.

Robustness of results

The majority of the data in the inventory that was used for calculating the environmental cost is monitoring data from the rig provided by either MD or DONG. Secondary data are retrieved from yearly environmental reports from the actual service providers used or specifications from actual technologies. For those data not available through these sources LCA assessments have been used. No data from environmental input/output tables have been used in the calculations. A set of key valuation estimates have been identified together with three sets of estimates for sensitivity testing of the final cost results. The valuation estimates addresses the total environmental costs associated with the impacts identified in the value chain.

Sensitivity testing using other set of valuation estimates does not change the conclusions.

Usability of NCA data for operational and strategic decision making

The environmental cost related to installation of a RENA Slop Water Treatment unit on the rig was considered, as an alternative to a conventional slop water treatment where all slop water produced during oil based mud (OBM) drilling is offloaded to onshore treatment. The calculation showed that installation of the RENA unit significantly reduced the environmental cost in the value chain related to OBM slop water handling.

The overall results show that NCA data developed in this pilot project have substantial value in operational and strategic decision making in businesses and may be used in a number of different ways:

- NCA data are highly usable to compare different technologies available. Consequently NCA data provides substantial value to decision processes as the monetary unit used is directly comparable with e.g. construction cost, operational costs, etc.

- The finding that upstream impacts from production of chemicals, fuels and steel are responsible for the majority of the total environmental cost in the value chain is also seen in other cases. This points at a general tendency that the majority of the environmental footprint in monetary terms relates to the primary production of materials. It also points to a need for a change in perspective for both businesses and regulators e.g. by promoting more reuse of materials, usage of circular business models and creating more awareness of and information on the upstream footprints in sourcing and designing.

- The distribution of the environmental cost in the value chain in general and specifically the relatively high share of the cost associated with upstream activities can open up decisions with stakeholders, e.g. with regulators and with suppliers. A key question here is where and how can we reduce the overall environmental emissions the easiest way with the resources available?

- NCA data can be used by suppliers and service providers for marketing and branding purposes, e.g. as comparison between products and services as illustrated with the slop water treatment approaches. Requesting data on the upstream emissions and stating that upstream emissions are a competitive issue when sourcing materials, businesses can engage in the transition towards more environmentally friendly materials and solutions as well as more transparent reporting

- Including NCA data as part of the decision basis helps qualify the discussions on design, investment and operation. NCA data may furthermore be used for documenting the sustainability of choice of technologies and decisions.

- NCA data provides new angels on the environmental reporting and the environmental management in general: Knowledge on the environmental costs in different parts of the value chain helps identify opportunities for continual improvement and reporting on social responsibility.

Overall, the pilot project has demonstrated that NCA data can provide business value to operational and strategic decision making.

1. Background & Objective

1.1 Background

Up until now Natural Capital Accounting (NCA) has primarily been tested through the Environmental Profit and Loss (EP&L) accounting approach[1] .

The NCA approach quantifies the societal costs and gains due to environmental impact in monetary terms from activities in part of or the full value chain (see figure below, which illustrate the value chain for drilling an offshore oil well).

FIGURE 1-1: ILLUSTRATION OF THE TIERS IN THE VALUE CHAIN OF CONSTRUCTING AN OFFSHORE OIL AND GAS WELL, WITH FOCUS ON THE CONSTRUCTION OF THE WELL. IN THE DOWNSTREAM TIER THE TRANSPORT AND HANDLING OF CUTTINGS, SLOP WATER AND CHEMICAL RESIDUALS ARE INCLUDED

EP&Lhave many advantages and serve as a new and valuable approach that supports informed decision making in businesses. One of the benefits is that they provide a holistic framework where impacts are assessed systematically. The DEPA Environmental Project No. 1561 from 2014 discusses that the EP&L approach also has drawbacks. These disadvantages are mainly centered around the fact that is the approach relies on old sector averages derived from environmental input/output (EIO) tables and LCA databases and thus does not necessarily capture the efforts done by business to distinguish itself from average performance. Futhermore the source and size of key figures used in EP&Ls to transform an inventory of e.g. resource usage or emissions into environmental and monetary impacts is often non-transparent nor available for readers. This poses a challenge for stakeholders to compare the societal footprint of two similar products. This non-transparency and use of averaged and often dated numerical data results in reduced usability of the

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[1] Danish Ministry of Environment, Environmental Protection Agency (2014a). Assessment of potentials and limitations in valuation of externalities: With special focus on Environmental Profit and Loss, Environmental Project No. 1561, 2014

Danish Ministry of Environment, Environmental Protection Agency (2014b). Danish apparel sector natural account, Revised version, Environmental project No. 1606, 2014

Danish Ministry of Environment, Environmental Protection Agency (2015). Natural capital accounting in the Danish apparel sector.

Danish Ministry of Environment, Environmental Protection Agency (2014). Novo Nordisk Environmental Profit & Loss Account

PUMA EP&L: http://about.puma.com/en/sustainability/environment/environmental-profit-and-loss-account

Kering EP&L: http://www.kering.com/en/sustainability/results

EP&L, for example in the re-design of products for lesser impact or in decision making and follow up on new strategy.

A more dynamic and user friendly approach is suggested in the DEPA report (1561/2014), focusing on providing transparent key figures and linking these – where possible - to actual operational data. This development project is aligned with this recommendation and aims to explore alternative NCA approaches.

1.2 Objective

The objective of this development project is:

- to develop and pilot test a NCA approach covering the construction of the offshore Hejre HA-1 production well using data from start-up to completion and focusing on societal costs in the full value chain from environmental impacts on air and water.

- to develop a tool that allows users to assess the environmental costs from a different well design in terms of different lengths of piping and choice of slop water treatment, level of flaring during testing and freqency of unintended discharges of small amounts of diesel oil and certain chemical types.

The well is part of the Maersk Drilling (MD) and DONG Energy (DONG) joint operation at the Hejre Field in the North Sea, where the Maersk Resolve mobile offshore drilling unit is under long-term contract. Construction of the Hejre HA-1 well is a 'High Pressure High Temperature' drilling operation (HPHT).

The project includes the following major activities

- **Scoping** of the pilot project including deciding types of input materials, types of emissions and tiers in the value chain to be included as well as the assumptions associated with both inventory and valuation methodology
- **Collecting and systemising** the best possible physical emission data in a **database** including monetary valuation estimates.
- Developing a **calculation tool** summing up the physical data and translating them into monetary values allowing comparison across footprints and different parts of the value chain as an **overview** of the results
- Performing **sensitivity testing** of results in order to assess the robustness of conclusions
- Developing an **interface tool** allowing to test the effect of different layouts of the well construction, choices of technologies and importance of unintended discharges of small amounts of diesel and certain chemical types and test usability of NCA data in operational and strategic decision making
- **Reporting**, including discussion and conclusion

Interface
Allowing for comparison of actual lay out with new layout of well

Overview of results
Using actual lay out of drilling operation & choice of technologies

Calculation tool
Using valuation data and performinig sensitity analysis

Database
Material input & emissions from value chain

FIGURE 1-2: OVERVIEW OF THE COMPONENTS OF THE PILOT PROJECT

It is important to keep in mind that this work is a **pilot project designed for demonstrating the business value from using natural capital accounting in operational and strategic business decision making**.

The pilot project has chosen a somewhat different approach than presented in NCAs like the EP&L's for NOVO Nordisk and PUMA: The focus is more on providing transparent methodologies and data for making the NCA site-specific, reusable and relevant to business decision making rather than providing the full account– that is a full cost estimate of all environmental cost to society. The pilot project is designed in a way that allows for later expansion of types of impacts, materials, technologies and more types of activities e.g. well service, administration onshore.

Emissions to air and discharges to water are generally key environmental focus areas for offshore operations. Therefore, the scope of this pilot is limited to environmental impacts from these two key areas that result from selected imported materials to the rig, such as steel, chemicals and fuel. Impacts throughout the value chain are included, which are both upstream, in the well construction and downstream in terms of waste handling onshore.

Note, that the delimitation to only impacts on air and water from usage of steel, chemicals and fuels is augmented in the demonstrational objective of and the resources available for this pilot project. As a consequence certain types of activities, materials and resulting impacts have been scoped out, see Chapter for more information 4.

In short, the project scope includes emissions to air from installing steel piping during the well construction, using fossil fuel combustion for rig, vessels, supply boats and helicopter and discharges to water. Upstream impacts are included in terms of emission to air and water from the production and transport of the imported materials cited. Downstream impacts to water and air are included as emissions from permitted discharge of Water Based Mud (WBM) drill cuttings to sea and Oil Based Mud (OBM) drill cuttings offloaded to shore for treatment.

Environmental consequences due to unintended discharges to the sea are included as 'thought experiments', to allow the assessment of hypothetical unintended discharges of different sizes and composition. In a similar way, impacts on the environment from hypothetical flaring during testing of the well is included (as HA-1 has not been tested). Finally, impacts from different technologies for offshore treatment of slop water are addressed in the pilot. Please refer to chapter 3 for more information on scope.

2. Why it matters to Maersk Drilling and DONG Energy

For this pilot study, Maersk Drilling (drilling contractor), DONG Energy (oil company) and COWI (consultant) have collaborated to construct a NCA covering the construction of the HA-1 well. This is part of Maersk Drilling (MD) and DONG Energy's (DONG) joint operation at the Hejre Field, where the Maersk Resolve mobile offshore drilling unit is under long-term contract.

For MD, Natural Capital Accounting (NCA) is consistent with their corporate commitments to protect the environment, play a leading role in promoting best practices in the industry, manage environmental matters as any other critical business activity and to manage and control risks systematically. MD has considerable financial exposure that is sensitive to changes in. among other issues, natural capital and related regulations. The company's operations rely on the one hand on natural resource inputs and on the other hand on having a substantial negative impact on certain parts of the natural capital stock. Natural Capital Accounting is considered an important stepping stone in providing a decision basis that enhances MD's ability to protect the environment and substantiate their social license to operate. This is by identifying externalities and impacts with the highest value to society and taking steps to minimize them, and in turn realising financial benefits in terms of reduced operational, reputational and regulatory risks.

DONG has an ambitious standard for managing their significant environmental aspects, driving their QHSE policy and ensuring that the focus is where the efforts have greatest effect. The QHSE policy includes the environmental statement: “We strive to minimise the resource consumption and environmental impacts and DONG works in accordance with this belief. Natural Capital Accounting has the possibility of supporting decision making and ensuring that the focus is at the right level and place”.

Considering the close collaboration between drilling contractor and oil company, embarking on a joint NCA exercise is logical.

MD and DONG are planning to use the NCA to substantiate and qualify the basis for decision-making, both from an operational and strategic standpoint. This is because NCA focuses on key issues of concern and provides comparative data to help management prioritise.

3. Introductory description of drilling operation

3.1 Introduction

This chapter gives an introductory description of the drilling operation of HA-1 in the Hejre Field. The actual activities performed during the drilling operation and the use of resources are described in details in chapter 6.

3.2 Rigs and location

The well is located in the Danish part of the North Sea close to the Norwegian Sector.

FIGURE3-1: THE HEJRE THE HEJRE JACKET (TO THE RIGHT) AND THE DRILLING RIG MAERSK RESOLVE (TO THE LEFT) & LOCATION OF THE HEJRE FIELD IN THE NORTH SEA HTTP://WWW.HEJRE.COM/EN/NEWS/ARTICLES/HEJRE-NEWSLETTER-AUGUST-2014

The Hejre Field is operated by DONG. Establishing the HA-1 well is part of the MD and DONG's joint operations at the Hejre Field, and the drilling rig is the Maersk Resolve mobile offshore drilling unit, see Figure3-2.

FIGURE3-2: THE MAERSK RESOLVE MOBILE OFFSHORE DRILLING UNIT
HTTP://WWW.MAERSKDRILLING.COM/EN/DRILLING-RIGS/JACK-UPS/MAERSK-RESOLVE

The drilling of the well penetrates the seabed using different diameters of sections. The type of geology penetrated,the diameter used and length of steel pipes are listed in the table below.

TABLE 3-1: SECTIONS, GEOLOGY AND LENGTH AND DIAMETER OF STEEL PIPE INSTALLED IN HA1 BASED ON DATA FROM DONG ENERGY. RIG TIME IS HOURS USED FOR DRILING THE SECTION, WHICH INCLUDES UP- AND DOWNTIME OF THE DRILLING EQUIPMENT. PLEASE ALSO REFER TO APPENDIX 1

Section diameter (inches)	Drilled length (meters)	Type of sediments penetrated
36	92	Quartz sand & clay stone
26	796	Quartz sand & clay stone
17 ½	1,672	Clay stone & lime stone
12 1/4	1,966	Clay stone & lime stone Clay stone w. natural radioactivity Chalk
8 ½	1,101	Clay stone & lime stone
8 ½ sidetrack	698	Clay stone & lime stone
Completion	-	-

3.3 Input materials & processes

Other than the drilling rig itself, supply vessels, helicopters and onshore activities, a substantial number of input materials are used for constructing an offshore oil well. These input materials include steel, electrical and mechanical components, fuel for generators, lubricant oils and chemicals for drilling and cleaning operations. Input materials are transported to the rig primarily by diesel driven vessels.

Helicopter fuel is transported to the rig to refuel the helicopters that bring input materials, equipment and crew to the rig. Diesel fuel is used for vessels transporting input materials to and from the rig. Diesel fuel is also used to generate power for operating the rig and support technologies such as the Mudcube unit and the RENA slop water treatment unit (see description of technologies below).

The drilling process includes installing steel pipes of different diameters and quality. The drilling process requires a substantial number of chemicals of which many are used in the drilling mud. Two different types of drilling mud – Water Based Mud (WBM) and Oil Based Mud (OBM) – are used depending on the section. Top sections are drilled with WBM and lower sections are drilled with OBM. After the well is constructed and casing is installed and cemented, production pipes are installed and the well is ready for testing/production.

Waste streams on the rig are treated by different technologies in order to reduce the impacts on the environment. In relation to the project scope the MudCube Unit and the RENA Slop water Treatment Unit are especially important:

- The MudCube unit (Mudcube) is an offshore technology for removing reusable drilling mud from the drilling. Drill cuttings containing mud are drilled out of the well. The Mudcube unit is primarily used when drilling with OBM. The Mudcube unit separates the reusable mud from the cuttings. When drilling with OBM the cuttings with the remaining OBM are classed as hazardous waste and are shipped onshore for treatment at Soil Recovery A/S. In other words, compared to conventional technology where all cuttings and mud are treated onshore, the Mudcube unit reduces the amount of waste that has to be handled onshore. Furthermore it allows for a high degree of reuse of the drilling mud and this results in lower energy consumption and reduced emissions to air. The cuttings and mud from the Mudcube unit are included in the project

- The RENA slop water treatment unit (RENA unit) is used for cleaning the slop water when drilling with OBM. Slop water is the water used for cleaning the rig and slop water contains cleaning agents as well as cuttings and chemicals spilled on the deck while drilling. Conventionally, all OBM slop water was transported onshore for treatment, but the relatively new RENA unit processes the slop water offshore by membrane filtration, which retains non-polar chemicals, oil soluble chemicals and particles >0.5 microns. The processed water may be discharged to sea in compliance with permits. The waste from the RENA unit - the retentate - is classed as azardous waste and is also transported onshore to Soil Recovery A/S for treatment. In other words, compared to conventional slop water treatment, where all the slop water is transported to onshore treatment, the use of the RENA unit reduces the amount of fluid that needs treatment onshore by more than 95% and thus reduced the overall energy consumption.

3.4 Emissions and waste streams

The well construction produces emissions to air and discharges to water along with a number of waste streams. Emissions and waste handling is highly regulated by the authorities and substantial control systems are in place to ensure compliance with permits.
The major types of emissions to air arise from the combustion of fossil fuels for energy production and flaring during testing of well. Permitted discharges to sea include cuttings, slop water and WMB

chemicals during drilling with WBM, as well of specific chemicals during cementing of the well. Furthermore, discharge of processed slop water from the RENA unit is permitted.

The cuttings containing OBM, slop water during OBM drilling as well as the retentate from the RENA unit are classed as hazardous waste and are shipped onshore for treatment at Soil Recovery A/S in Nyborg. The treatment at Soil Recovery consists of a heating process which transfers the contaminants to either a water phase or an oil phase. The output from the oil phase may be reused for combustion or as an ingredient for new drilling mud. Output from the water phase is eventually handled at the local sewage water treatment plant. The cleaned cuttings are disposed of at a local landfill. In addition, activities on the rig produce household waste and chemical waste from maintenance activities.

After completion, the well is sometimes tested in accordance with permits. During this testing phase, a substantial volume of gas is flared causing emissions to air. The flaring gas contains methane and other volatile hydrocarbons from the crude oil.

3.5 Unintended discharges

All operational activities are risk assessed with a focus on, among others issues, avoiding unintended discharges to the sea. Unintended discharges are therefore rare on the drilling rig.

4. Overall scope

4.1 Balancing scope with intent of a pilot project

As mentioned, this project is a pilot study designed to demonstrate an alternative NCA approach and focuses on selected specific types of activities and impacts and uses those data and results to demonstrate the business value of using NCA data and tools. It was therefore a conscious choice to delimitate the scope and at the same time ensure a high data quality and full transparency in order to use the results to design future value creating NCA approaches.

These considerations entail that the estimated cost to society from the activities included in the scope do not amount to a full total of the environmental impacts from construction of the specific oil well HA-1.

In the delimitation, it was agreed that only the drilling activities and activities related to this was included. As the lifespan of drilling rigs is high, the drilling of the well in question only consumes a very small share of the total use of the rig. Thus the impacts on the environment from design, sale, production, maintenance, use beyond the drilling of the specific well itself and decommissioning of the rig is not included in the scope. Impacts on e.g. land use and biodiversity is not included in the scope of the project. However, the stated activity types do impose a significant impact on the environment.

All the supporting and administrative activites onshore and on the rig are also scoped out of the pilot project. The onshore activites needed for operating the rig includes a share of the office activities undertaken by MD and DONG and their consultants and include onshore storing facilities. The impacts comes from design, production/contruction, maintanance and decommisioning of office space and transportation of the staff from their work. These activities are not included in this scope, due to the demonstrational focus of the pilot project and a wish to test the effects of which specific materials are used to construct the well. However, they do clearly pose an impact to society and the environment as was seen in the Novo Nordisk EP&L[1]. Only fuel consumption due to transportation and accomodation of onshore staff visiting the rig is included.

The following chapters describe what is included in the scope in the project. Detailed information of input materials streams, emissions to air and discharge to water and impacts on the environment are described in details in chapter 6. All other impacts on the environment,whether upstream or downstream, than those mentioned in the following chapters are scoped out of the project. Examples of what is not included in scope are presented in Table 4-1.

TABLE 4-1: EXAMPLES OF WHAT IS NOT INCLUDED IN THE PILOT PROJECT SCOPE.
PLEASE NOTE, THAT THE LIST NOT FULLY EXHUSTED, AND REFER TO THE TEXT FOR INFORMATION OF WHAT IS INCLUDED IN SCOPE

- Design, production, transport and decommissioning of both drilling rig, production platform, vessels, helicopters and other transport or operational agents
- Design, production, operation, maintenance and decommissioning of onshore activities supporting activities on the rig, e.g. offices, storage facilities, supplier of materials not included in scope
- Testing of the HA-1 well and production of oil from the HA-1 well. Flaring following testing of the well is addressed as a 'thought experiment', allowing a choice of flaring volume
- Subsea operations and subsea impacts
- Discharge of water from the rig, except from the slop unit
- Unintended releases of crude oil e.g. from blow-out
- Marine acoustic pollution
- General land use impacts in the full value chain, including e.g. landfilling of treated drill cuttings
- Stand-by boats and equipment including emergency drills etc.
- All types of waste except drilling waste (mud and cuttings) and slop water
- Impacts on human capital are excluded from scope
- The impact that the use of resource will have as they cannot be used alternatively. In other words, if a non-renewable resource is used for the purpose of this project it cannot be used for other applications. The difference in the value that the resource represents, based on the usage, is outside of scope due to the lack of knowledge of alternative uses at the location but also the general lack of societal assessment of non-renewable resources. This will also be the case for renewable resources like water, however, the value will be lower.

4.2 Types of input materials and processes included in scope

To limit the scope whilst ensuring quality data collection, the following criteria were used to select which material inputs to be included:

- Material inputs widely used
- Material inputs of high volume
- Material inputs known to have major environmental impact in the value chain

Based on the above the following input materials to the rig are included within the scope:

- Steel pipe installed in well
- Diesel used for operation of rig
- Helicopter fuel used for helicopter transportation (crew and materials)
- Diesel used for transportation of input materials by supply vessel as well as waste to/from the rig and onshore to transport waste to onshore treatment plants
- Fuels/energy used in onshore treatment processes of waste from drilling and constructing the well
- Chemicals used in the drilling process

Input materials included are described in details in chapter 6.

The following processes and technologies are addressed specifically in the assessment in terms of environmental impacts from emissions to air and water:

- The drilling operation in terms of diameter and length of each section and the material used and associated emissions.
- Handling of cuttings and drilling mud
- Handling of slop water offshore, including operation of the RENA Slop Treatment Unit when using OBM compared to the conventional handling of OBM slop water where all slop water is shipped to shore for treatment.

Unintended discharges and flaring during testing are included as thought experiments, to allow estimation of societal cost for a variable size and type of spill and/or flaring.

4.3 Type of emissions included in scope

As the study is a pilot project designed to demonstrate the value to business of using NCA data, a selection of emission types to be included was performed. The selection took into account, among other aspects, the availability of data and the relevance of the emissions in terms of business and stakeholder focus. In the following sections emission types included in the pilot study are presented, as each emission stream is described in detail in chapter 6.

4.3.1 Emissions to air

Emissions to air are included in scope for each of the material streams in the full value chain. Emissions to air are based on actual site-specific data (rig and offshore treatment of drill cuttings and mud) or on LCA data (production and transportation of input materials transported to the rig).

In addition, emissions to air from flaring during well testing is included as a thought experiment.

The following parameters are in focus both upstream, in operation of the rig (including transportation to and from the rig by sea and air) and downstream:

- Green House Gases (GHG, consisting of CO_2, N_2O and CH_4), estimated as CO_2 equivalents
- SO_X (SO and SO_2) estimated as SO_x
- NO_X (NO and NO_2) estimated as NO_x
- Particular matter, PM as $PM_{2.5}$

There have been considerations with regards to including black carbon in the valuation. Black carbon (BC) is the strongest light-absorbing component of particulate matter (PM), and is formed by the incomplete combustion of fossil fuels, biofuels and biomass. BC is emitted directly into the atmosphere in the form of fine particles ($PM_{2.5}$). Thus BC is part of the PM emission[2]. The $PM_{2.5}$ fraction has been chosen instead of e.g. total suspended particles (TSP) as this would underestimate the effect of smaller particles. See more information of the environmental effects of particulate matter in Chapter 5.2.

Valuation estimates for black carbon have been searched for from DEPA, DEA and DCE sources with limited results. Black carbon emissions are not monitored and may only be estimated by using emissions factors. As black carbon is part of the $PM_{2,5}$ fraction of the particular matter emitted, the valuation of the impacts following emission of black carbon assume that black carbon is part of the valuation estimate related to the PM emission. If valuation of the BC is combined with a valuation of the PM, the valuation of BC will be included twice. Therefore, the decision has been made to scope out black carbon. Please refer to Chapter 8 for more information on the valuation of PM.

4.3.2 Discharges to water

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[2] http://www3.epa.gov/blackcarbon/basic.html

The following types of water discharges have been included in this scope:

Upstream:

- Discharge to fresh water and sea in relevant parts of the value chain from discharge of sewage water

Well construction:

- Permitted discharge to sea from the construction of the well
- Unintended discharge from the rig to sea

Downstream:

- Discharge to fresh water and marine water in relevant parts of the value chain from discharge of sewage water

Discharges to water bodies are based on actual site specific data (monitoring data from the drilling operation and onshore treatment of drill cuttings, mud, slop water and retentate or on LCA data. Parameters included in assessing the impacts from emissions to water varies, and approaches on impact assessment for chemicals and unintended discharges are discussed in details in chapter 6.3 and 7.2.

5. Overall methodology

5.1 Value chain approach

During the course of well construction, many input materials are used on the rig for different purposes. Input materials used on the rig impact the environment, not only while utilized on the rig, but also when being produced and transported to the rig and later when disregarded as waste. The overall environmental impact may be illustrated by looking at the value chain of the operation and assessing the environmental impacts associated with each step.

The following illustration is a simplified value chain with just four steps (tiers). The first tier includes the production of raw materials and transport needed to reach the second tier – the production of the input materials and transport to the rig for the drilling operation. The third tier is the drilling operation itself. The last thier represents the downstream activities where the waste from the drilling is transported and treated.

FIGURE 5-1: VALUE CHAIN TIERS ADDRESSED IN THE PROJECT

5.2 Using environmental emissions for valuating environmental impacts

The activities in each tier have a number of emissions that result in various environmental impacts. These impacts have a societal cost, which may be estimated based on the actual emission and a valuation estimate, see chapter 8.

In accordance with the scope the following types of emissions throughout the value chain are included:

- Air emissions: GHG, SO_X, NO_X and PM
- Freshwater usage for production of inputs and treatment of waste
- Marine areas negatively impacted from permitted discharges and unintended discharges

The activities and environmental impacts included in a value chain perspective are illustrated below (compared to Figure 1-1 tiers 1 and 2 are added up in this illustration as they both relate to the upstream activities).

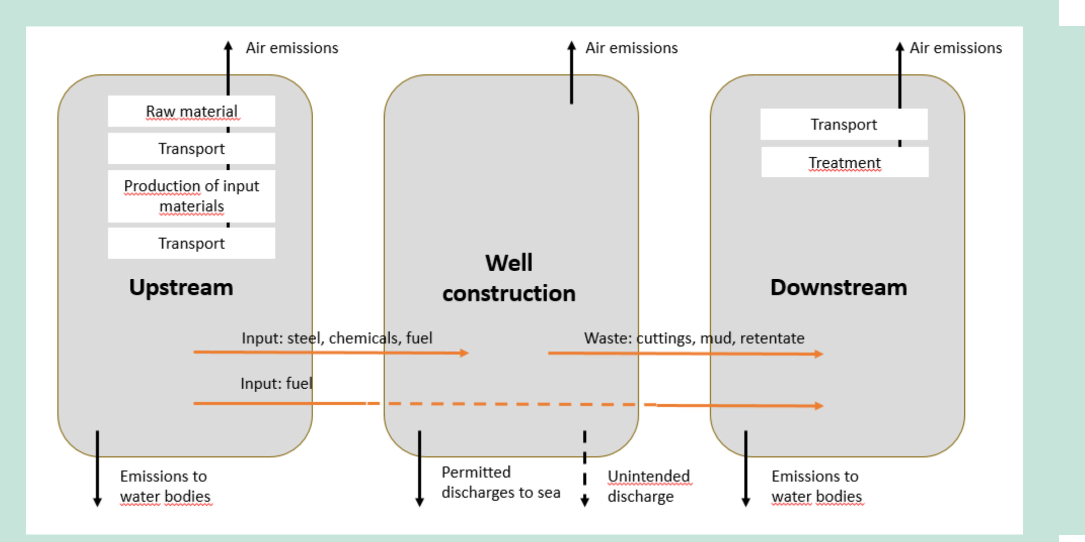


FIGURE 5-2: ILLUSTRATION OF WHAT IS INCLUDED IN THE ANALYSIS. THE SMALL LIGHT GREY BOXES INDICATE THE DIFFERENT ACTIVITIES INCLUDED IN THE GIVEN PART OF THE VALUE CHAIN. ENVIRONMENTAL IMPACTS ARE INDICATED THROUGH EMISSION TO AIR, MARINE WATER AND FRESH WATER. THE ORANGE LINES INDICATE THE RESOURCES BEING PRODUCED, BEING USED ON THE RIG AND BEING DISPOSED/TREATED OFF THE RIG. IMPACTS FROM FUEL COMSUMPTION DOWNSTREAM FOR TRANSPORT AND TREATMENT OF THE WASTE STREAMS ARE INCLUDED IN THE FULL VALUE CHAIN. PLEASE NOTE THAT OPERATION OF THE RIG AND OPERATION OF VESSELS AND HELICOPTERS TRANSPORTING INPUT MATERIALS AND PERSONNEL BETWEEN ESBJERG HARBOUR AND THE RIG ARE INCLUDED IN THE WELL CONSTRUCTION TIER.

The emissions to water bodies related to the activities both up and downstream and during well construction are addressed as follows:

- **Upstream and downstream emissions to water:** Emissions or regulated discharges to fresh water and marine water from activities in the upstream and downstream tiers are addressed using the water usage as a basis assuming a certain share of the water used that ends up as sewage water. It is not possible from the LCA data to assess the division of emissions to fresh waters and marine water respectively, so this is why emissions to water of any kind are addressed as one. The categories **'upstream emissions to water', 'downstream emissions to water'** and **'up and downstream emissions to water'** are used with the following abbreviations **'UEW', 'DEW'** and **'U&DEW'**

- **Emissions/discharges to water during well construction:** The emissions to water during the well construction consist of permitted discharges to sea and unintended discharges to sea. Permitted releases to fresh water bodies during the well construction phase are estimated to be negligible (as the majority of the activities are happening on the offshore rig). The discharges to water in terms of permitted discharges to sea during the well construction phase are addressed through the category: **'Well construction – Emission/discharges to water**', abbreviated **WC EW**. Unintended discharges to sea are addressed separately as **'Unintended discharges to sea'**, abbreviated 'U**D**'

Environmental impacts from these activities are among others

- Air :
  - GHG emissions impact the global climate by creating a heat-trapping effect by absorbing energy and thus reducing the release of heat back to the atmosphere. This results in so-called global warming. On a global scale emission of GHGs is considered to be a significant environmental and human challenge and global initiatives are taken to control and reduce emissions of GHG. The main GHGs are CO_2, CH_4 and N_2O.

  - Emissions of SO_x cause a range of significant human health issues, notably effects on breathing and related respiratory concerns. High levels of SO_x can aggravate existing cardiovascular diseases in particular, among children, elderly and people with chronic respiratory stress functions. Environmental impacts of SO_x emissions include acidification of streams and lakes and corrosion of buildings.
  - Emission on NO_x causes acidification and eutrophication which lead to fundamental trophic changes in aquatic and terrestrial ecosystems. Eutrophication caused by NO_x emissions is currently one of the main reasons for changes to the vegetation of nutrient-poor and oligotrophic ecosystems such as heathlands and coastal dune meadows. Human health issues related to NO_x emissions include inflammation of respiratory organs and NO_x contribute to ozone formation.
  - PM emissions consist of a variety of very small particles and droplets, made up of a number of components. PM emissions and especially the very fine particles named black carbon are known to cause human health problems related to the lungs and the heart by impacting and reducing their normal functions. PM particles can also enter reactions with other chemicals such as SO_x and NO_x and thus add to the environmental effects of these gasses.

- Freshwater: The use of freshwater in production and waste treatment can have severe effects on local and regional hydrological cycles and thus potentially cause ecosystem stress and shortage of drinking water for human populations. Local exploitation of freshwater resources can lead to a lowering of the groundwater table which causes changes to surface water hydrology and ecosystem changes because of reduced water availability for biological cycles. Water used for waste treatment of mud cuttings, retentate and waste disposal will have negative environmental effects related to eutrophication and pollution, which may have negative impacts on the environment, ecosystems and the availability of drinking water.

- Marine water: Discharge and spills of environmentally hazardous substances can have negative environmental effects both locally near the discharge/spill but also further away, depending on marine currents transporting substances to other marine areas and potentially to coastal waters. The environmental effect of discharges and spills depends on the types of substances, their toxicity and the rate of their natural degradation in the marine environment. Typical environmental effects include direct toxic effects on marine organisms, clogging of respiratory organs in marine animals and sedimentation on marine organisms, leading to reduced food availability, cover, growth and reproduction.

5.3 Overall approach on data sources, collection and compilation

To ensure the usability of the results for operational and strategic purposes, the quality and relevance of data in a business context have had key priority in the project.

Below the priority of data sources used in the project is illustrated as levels of increasing data quality. To give an example, site specific data have a higher quality that e.g. data retrieved from life cycle assessments (LCAs) or environmental extended input-output data (EEIO). EEIO data is based on statistical data on the trade of goods between sectors and/or economies and reflects production and consumption structures within one or several economies. LCA data and EEIO data are often based on old(er) sector averages and is as such not necessarily descriptive of the actual set up.

Data from a lower level is used only when there are no data available in an upper level.. In this project data from the first four groups have been used, with the majority of data being available from the first group. In the next section a more specific description of the data mining approach is described. The prioritisation of data includes both operational data and conversion factors.

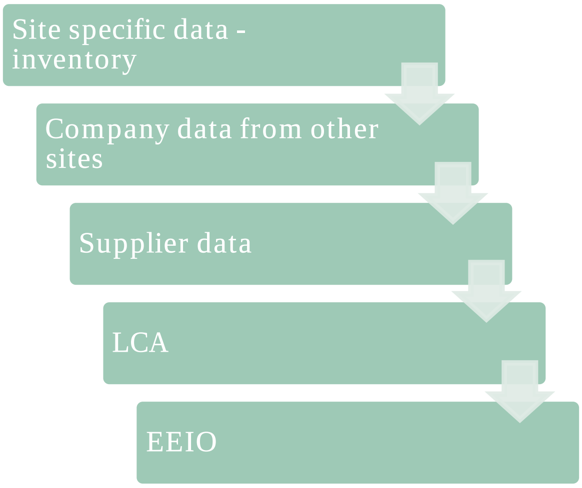


FIGURE 5-3: PRIORITY OF DATA SOURCES ON OPERATIONAL DATA AND CONVERSION FACTORS

5.4 Addressing actual operation and scenarios related to technologies and events

In the following chapters the inventory of the actual operation and usage of input materials are described and extended to both upstream or downstream activities and emissions where relevant. These data are used for estimating the cost to society from constructing the actual well.

Furthermore these data are used as basis for estimating unit-prices, e.g. cost pr. meter well of a given section. These unit-prices combined with scenarios on slop water treatment, unintended discharge and flaring during testing of the well allows the users to calculate the societal cost resulting from a different well design.

6. Inventory for the well construction

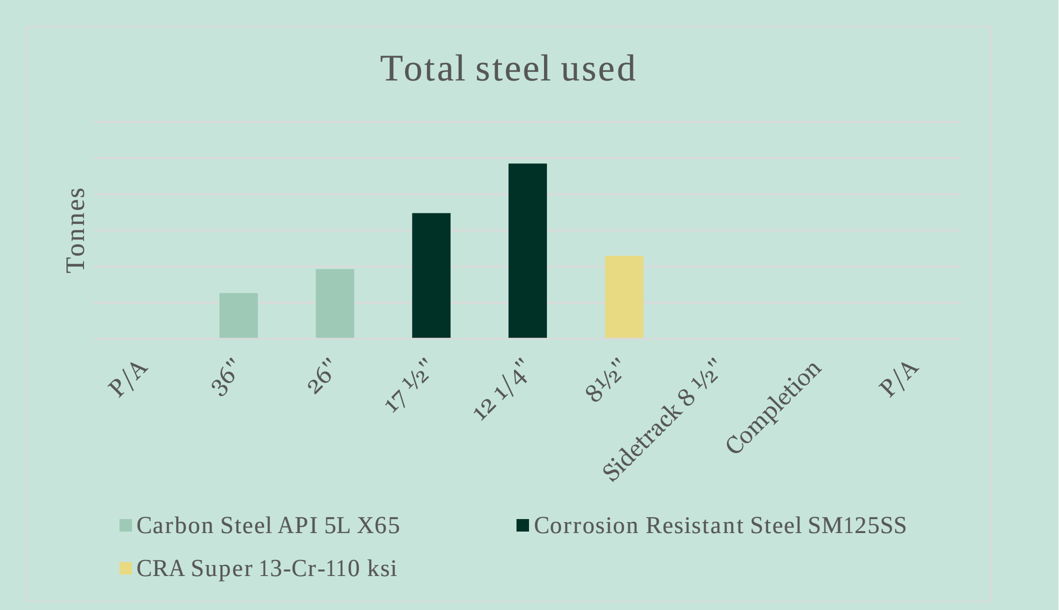
This chapter describes the types of input actually used in the well construction in terms of materials used, emissions and impacts following both the drilling operation as well as related upstream and downstream activities.

6.1 Steel

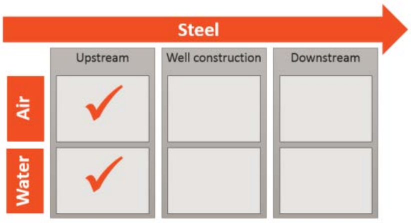
Three types of steel are used on the rig to construct the well. The pipe installed in the well is high quality steel, typically pre-ordered in the correct lengths and diameters.

The steel types are Carbon Steel API 5L X65, Corrosion Resistant Steel SM125SS, CRA Super 13-Cr-110 ksi. The actual diameters and lengths of steel piping used in the HA-1 well are presented in chapter 3.2.

In the figure below the total usage of steel in the well is divided according to the section sizes of the well. The steel is used in all of the sections of the well except in the side track. The steel origins from Italy, France and UK. The majority of the steel is Corrosion Resistant Steel SM125SS, which is used in the 17.5 and 12.25 inches sections.



FIGUR 6-1: OVERVIEW OF THE STEEL CONSUMPTION DIVIDED BY SECTIONS



Upstream environmental impacts from production and transport of the steel pipe are included in scope. As the amount of steel waste produced during drilling operations is negligible, the emissions and impacts from the installation of the steel in the subsurface are related to the energy used for running the drill. Consequently, operational impacts related to steel are included under the fuel consumption on the rig, section 6.2. The included impacts from use of steel in the well are illustrated in the figure to the left.

In the following chapters the assumptions applied and the environmental emissions are described.

6.1.1 Upstream

Upstream activities includes mining, production and transport of the steel throughout the supply chain (until the steel reaches Esbjerg Harbour).. The upstream emissions to air and the water use are estimated using LCA[3]. See Appendix 4 for description of the LCA approach.

The LCA uses Europe as the production site and assumes that raw material originates from China. Transportation of the raw material from the mines to the production site in Europe and transportation of the final product to Esbjerg Harbour is included in the LCA assessment. Transportation is assumed to be either by vessel or by truck. The LCA addresses impacts related to air emissions and water usage according to scope. The LCA data for the three types of steel are summarised in the table below:

TABLE 6-1: UPSTREAM LCA DATA FOR THE THREE TYPES OF STEEL. PLEASE NOTE THAT THE ACUTAL TYPE OF STEEL USED IS APPROXIMATED BY OTHER STEEL TYPE IN THE LCA. THE DATA INCLUDES BOTH PRODUCTION OF RAW MATERIAL AND STEEL PIPES AS WELL AS TRANSPORTATION FROM PRODUCTION SITES TO ESBJERG HARBOUR

Emission parameter	Unit	Steel type		
LCA Approximation		**Steel**	**Stainless Steel grade 430**	**Stainless steel grade 316**
Actual used		Carbon Steel API 5L X65	Corrosion Resistant Steel SM125SS	CRA Super 13-Cr-110 ksi
CO_2	kg per kg steel	2.68	3.39	3.26
NO_x	g per kg steel	4.01	9.84	11.9
SO_x	g per kg steel	5.67	15.5	40.5
$PM_{2.5}$	g per kg steel	0.93	2.90	5.57
Water usage	l/kg steel	5.52	367	64.7

As presented in the table, the upstream emissions pr. kg steel varies from steel type to steel type – in some cases close to a magnitude. In the table below the emissions following upstream activities related to production and transportation of the three types of steel to Esbjerg Harbour are summarized:

TABLE 6-2: UPSTREAM EMISSIONS AS % OF TOTAL EMISSIONS FROM PRODUCTION AND TRANSPORT OF STEEL USED IN THE WELL.

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[3] Individual LCA analysis on steel, COWI

Steel - total	**Sum of three types of steel**					
Emission	Upstream Tiers					
	Unit	Production of raw materials	Transport	Production of input materials	Transport to Esbjerg Harbour	Total
NO$_x$	%	82	15	1	2	100
SO$_x$	%	90	8	1	1	100
GHG	%	92	2	2	4	100
PM$_{2.5}$	%	88	8	2	2	100
Water usage	%	95	1	1	3	100

The discharged water from mining is not estimated in the LCA, but may be estimated from environmental reports and others sources from the mining industry. Water is used by the minerals industry for operational activities including:

- transport of ore and waste (in slurries and suspension)
- separation of minerals through chemical processes
- physical separation of material such as centrifugal separation
- cooling systems around power generation
- suppression of dust, both during mineral processing and around conveyors and roads
- washing equipment
- de-watering of mines

In the publication 'Australian mining: Water in mining and industry', it is stated that water use by the mining industry has been relatively steady. According to the Australian Bureau of Statistics (ABS) water accounts, the Australian mining industry consumed 508 GL in 2008–2009. Furthermore, it states that in 2008–09, the mining sector had a regulated discharge to the environment of 37 GL[1]. This equals 7.3 % of the water usage in the sector.

The mining company Rio Tinto's mines aluminum, copper, iron ore, coal and uranium spanning all over the world, but is concentrated in Australia and North America [2]. According to the annual report from Rio Tinto, the company's water balance worldwide has a water withdrawal of 1,236 GL and 428 GL of water in ore that is processed. On the output side it is reported that 98 GL is entrained in product or process waste and 4.5 GL is sent to third parties. According to the same report, evaporation and seepage accounts for a total of 596 GL.

The evaporated water is as such clean, but from a societal perspective the water is not available for other users in the downstream parts of the water catchment. Furthermore the evaporation process produces a waste of unknown environmental hazardousness and may pose an environmental risk at a later stage.

As a conservative approach, it is assumed that all the cited water discharges/outputs requires some kind of treatment in order to achieve zero impact or a minimal impact on the environment. It is

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[1] 'Australian mining: Water in mining and industry', by Ian Prosser, Leif Wolf, and Anna Littleboy, (http://www.publish.csiro.au/?act=view_file&file_id=9780643103283_Chapter_10.pdf)
[2] (http://www.riotinto.com/documents/ReportsPublications/RTandWater.pdf).

assumed that approximately 50% of the water used requires treatment. It is further estimated that the water discharge is equal to 50 % in average of the water usage in all other upstream activities in the steel production. It has not been possible to find a reliable estimate for the valuation of the unknown effects of evaporation.

6.1.2 Well construction & downstream

Transportation of steel to the rig and installation of the steel in the seabed results in various emissions to air and water. For analytical purposes and to avoid double counting, these emissions are addressed in other sections of this chapter. Air emissions from supply vessels from Esbjerg Harbour to the rig and installation of the steel in the seabed are addressed in chapter 6.2. Installation of steel in the well results in the production of 'waste' in the form of cuttings and drilling mud. Some waste streams are discharged within existing permits, others are treated in the Mudcube or RENA unit before permitted discharge and the remainder is shipped onshore for treatment. These emissions are addressed in chapter 7.

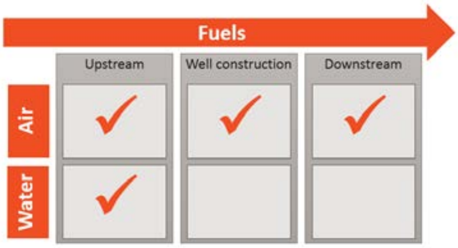
As this pilot study, focus is on the drilling operation and does not include oil production nor the decommissioning phase, environmental impacts from installation of the steel in the subsurface are set at zero.

6.2 Fuels and electricity

During the drilling operation, diesel is used for supply vessels transporting supplies and backloading waste to and from the rig, for operating the rig as well as helicopter refueling.

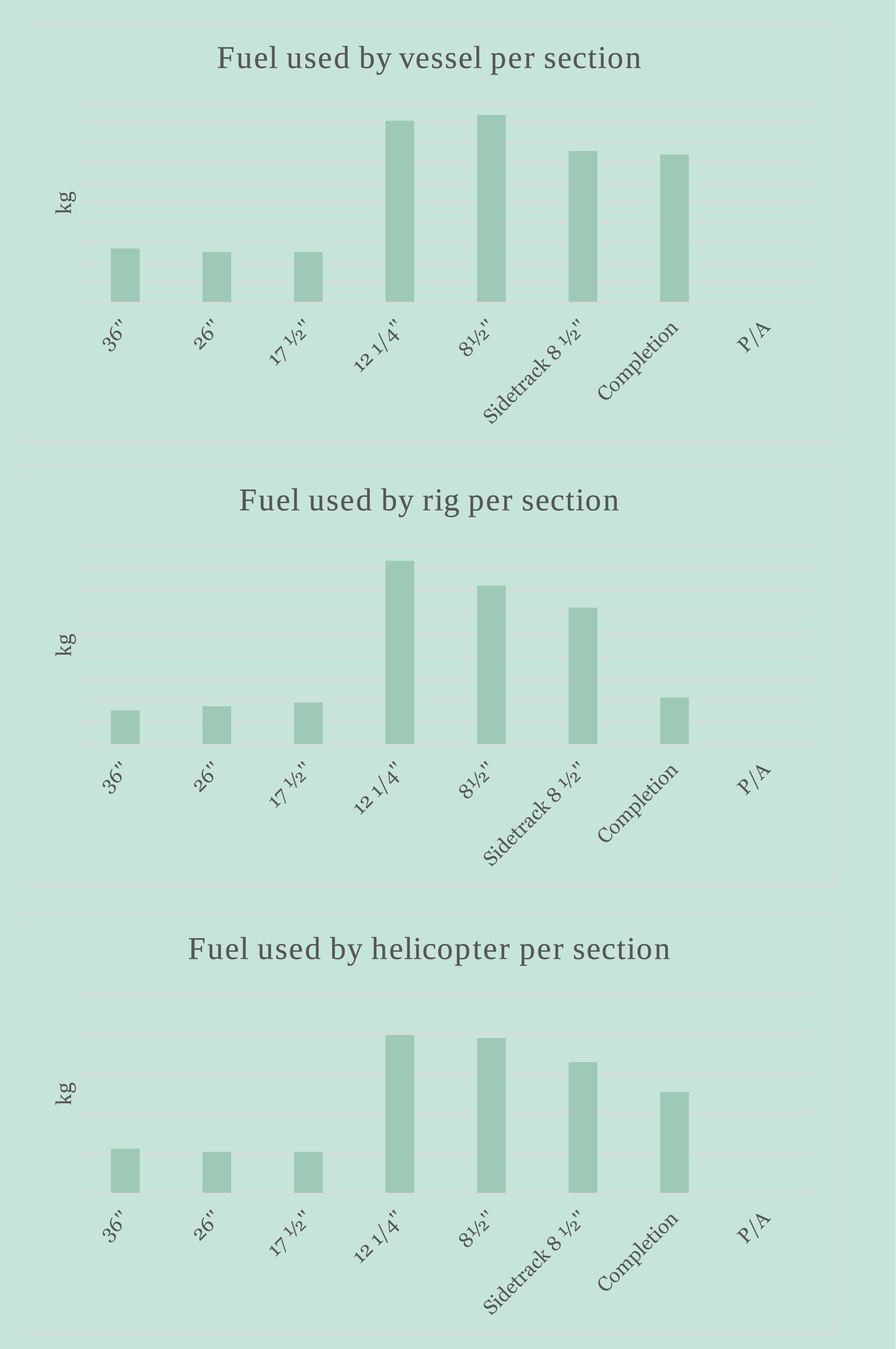
Diesel is also used for transporting drill cuttings, mud and slop water to shore and from Esbjerg Harbour to Soil Recovery A/S in Nyborg. Electricity is used during the waste treatment process in Soil Recovery A/S.

Impacts on the environment from emissions to air and water related to fuels and electricity are addressed in the next sections.



As illustrated in the figure to the right, the upstream tier includes emissions to air and water from extraction of crude oil and transportation and refining of fuels and energy. The well construction tier includes emissions to air from fuel consumption during the drilling operation, as emissions to water due to fuel consumption is set to zero due to stringent environmental regulations. The downstream tier includes emissions to air from use of fuels and electricity related to waste transportation and handling.

The figure below provides an overview of fuel consumed during construction of each section of the well:


Fuel used by vessel per section

Fuel used by rig per section

Fuel used by helicopter per section

FIGUR 6-2: OVERVIEW OF FUEL CONSUMPTION FROM THE VESSEL, RIG AND HELICOPTER DIVIDED ON SECTIONS.

6.2.1 Upstream

The emissions to air and water from extracting crude oil, refinement into diesel and helifuel and the transportation between production sites and to the consumer (in this case to Esbjerg Harbour) are assessed through LCA[4]. See Appendix 4 description of the LCA approach.

The fuel used for the operation of the rig, for vessels, helicopters and for on land transportation of the waste, originates from Denmark and is based on crude oil from the North Sea. The transportation of the crude oil from the production well to the refinery and transportation of the final product to Esbjerg is assumed in the LCA to be by either by vessel or truck.

The electricity used downstream in the treatment at Soil Recovery is produced in Denmark and emissions are estimated by LCA[5].

The estimated upstream emissions to air and water from production of diesel, helifuel and electricity are summarised in the tables below:

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[4] Individual LCA analysis (Diesel, heli-fuel), COWI

[5] Individual LCA analysis (Electricity), COWI

TABLE 6-3: UPSTREAM EMISSIONS FROM PRODUCTION AND TRANSPORT OF FUELS, BASED ON LCA

Fuel	**Diesel fuel – Rig and Vessel**				
Emission	Upstream Tiers				
	Unit	Production of raw materials	Transport	Production of diesel fuel	Transport to Esbjerg Harbour
NO_x	kg/tonne fuel	1.99	0	0.6	0.01
SO_x	kg/tonne fuel	2	0	0.6	0.01
GHG	kg/tonne fuel	334.5	0	98	6
PM2.5	kg/tonne fuel	0.3	0	0.09	0.002
Water usage	m^3/tonne fuel	121	0	36	0.2

Fuel	**Helicopter fuel**				
Emission	Upstream Tiers				
	Unit	Production of raw materials	Transport	Production of heli-fuel	Transport to Esbjerg Harbour
NO_x	kg/tonne fuel	2.7	0	0.8	0.008
SO_x	kg/tonne fuel	2.3	0	0.7	0.007
GHG	kg/tonne fuel	354	0	104	5.96
$PM_{2.5}$	kg/tonne fuel	0.3	0	0.1	0.002
Water usage	m^3/tonne fuel	154	0	45	0.2

Please note that the LCA divides the total emissions into different upstream activities and assumes that emissions during transport between production of raw materials and final products are zero.

The discharged water upstream is estimated using the water usage from the LCA and adjusting to the actual water discharge. According to Shell's environmental report (2013) for their refinery in

Fredericia, Denmark, the water usage was 545 m^3 and a total of 638 m^3 was discharged[6]. The discharged water includes water extracted from the oil. This indicates that 17% more water is discharged compared to the water usage (ratio 1.17). For the DONG oil pipe in Esbjerg (where the crude oil arrives to Denmark) the ratio is close to 1[7]. For the purpose of calculating the environmental costs it is assumed that an average ratio = 1 between water usage and water discharge may be used for all upstream fuel productions and that no significant amount of waste water is related to transport of fuels on sea and land.

6.2.2 Well construction

A diesel based generator on the rig produces electricity to operate the rig, as well as providing electricity for offices and accommodation and for operating the Mudcube unit and the RENA slop water treatment unit. The emissions from the RENA unit are addressed in the scenarios chapter 7.

During the well construction helicopter fuel and diesel are imported to the rig or supplied to the vessel or helicopter in Esbjerg Harbour.

Please note, that as data for the fuel consumption for the vessels and the helicopters were only made available for 2014, it is assumed that a similar level of fuel consumption is applicable for 2015.

As helicopters should never run empty for safety reasons, the helicopter tanks fuel onshore before take-off and may refuel on other rigs visited on the same trip. Therefore, the actual usage of helicopter fuel *related to the well construction* may differ from the data in the table. However, it is assumed that the helicopter fuel consumption is equal to the monitory data from DONG.

Permits do not allow discharge of fuel to the sea. Unintended discharge of fuel is addressed in chapter 7.2.

In the table below the emissions from combustion of fuels during well construction and for operating the rig, vessels and helicopters are presented. The total emissions are divided between sections.

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[6] http://s07.static-shell.com/content/dam/shell-new/local/country/dnk/downloads/pdf/about-shell/miljoredegorelse-2013.pdf

[7] https://assets.dongenergy.com/DONGEnergyDocuments/com/Sustainability/performance_data.pdf

TABLE 6-4: DIVISION OF EMISSIONS BY SECTIONS. ALL EMISSIONS FROM COMBUSTION OF DIESEL AND HELICOPTER FUEL DURING WELL CONSTRUCTION AS A% OF TOTAL EMISSIONS. UPSTREAM EMISSIONS ARE NOT INCLUDED.

Vessel		**Sections**								
Emission	Unit	P/A	36"	26"	17 ½"	12 1/4"	8 ½"	Side track 8 ½"	Completion	Total emission
NO_x	%	-	7	6	6	22	23	18	19	100
SO_x	%	-	7	7	7	16	24	19	20	100
GHG	%	-	6	6	6	22	22	18	19	100
$PM_{2.5}$	%	-	7	6	6	21	23	19	18	100

Rig		**Sections**								
Emission	Unit	P/A	36"	26"	17 ½"	12 1/4"	8 ½"	Side track 8 ½"	Completion	Total emission
NO_x	%	-	5	6	7	29	25	21	7	100
SO_x	%	-	5	6	7	29	25	21	7	100
GHG	%	-	5	6	7	29	25	21	7	100
$PM_{2.5}$	%	-	5	6	7	29	25	21	7	100

Helicopter		**Sections**								
Emission	Unit	P/A	36"	26"	17 ½"	12 1/4"	8 ½"	Side track 8 ½"	Completion	Total emission
NO_x	%	-	7	6	6	23	23	19	15	100
SO_x	%	-	7	6	6	23	23	19	15	100
GHG	%	-	7	6	6	23	23	19	15	100
$PM_{2.5}$	%	-	7	6	6	23	23	19	15	100

6.2.3 Downstream

Fuel and electricity consumption downstream is used for transporting cuttings, mud, residual chemicals and retentate from the RENA unit to Soil Recovery A/S in Nyborg and for the treatment of the mentioned waste types. Details on emissions from Soil Recovery A/S are found in Appendix 2.

According to information from DONG,diesel fuel consumption for vessel transportation of waste is 2.4 kg diesel per tonne of waste. The diesel consumption pr. truck trip from Esbjerg Harbour to Soil Recovery in Nyborg is 3.45 kg diesel pr. tonne of waste.

TABLE 6-5: DOWNSTREAM EMISSIONS FOR TRUCK TRANSPORTATION OF DRILL CUTTINGS IN GRAMS PER KM (CUTTINGS, MUD AND RENTENTAT). EMISSIONS FROM VESSEL TRANSPORT ARE INCLUDED UNDER VESSELS IN PREVIOUS TABLE 6.4

Downstream emissions for truck transport of drill cuttings		
	Unit	
NO_x	g/km	5.27
SO_x	g/km	0.03
GHG	g/km	864.15
$PM_{2.5}$	g/km	0.04
Water usage	m^3 per tonne*km	0.69

The table above only includes the results for transport by truck as in the actual situation. The transport by vessel is included under well construction. When the slop handling scenarios are analyzed, the emissions from the supply vessels for transport of slop water are separated from the other use of the vessels, see chapter 7.1.

In addition to these emissions the upstream impacts from the production of the diesel consumed for the transportation should also be taken into account. These are covered in the total emission from the transportation and treatment of the waste in Table 6-6.

Electricity and diesel used on Soil Recovery are produced in Denmark. A minor part of the energy used at the treatment plant is based on recovered oil from the waste treatment. This reuse of recovered oil is included in the analysis. It is assumed that environmental impacts due to downstream fuel emissions to water bodies are negligible and they are therefore set to zero.

TABLE 6-6: DOWNSTREAM EMISSIONS FROM TRANSPORTATION AND TREATMENT OF OBM DRILL CUTTINGS ONSHORE AT SOIL RECOVERY, INCLUDING EMISSIONS IN UPSTREAM PRODUCTION AND TRANSPORTATION OF FUEL AND ELECTRICITY USED FOR TRANSPORTATION AND TREATMENT OF THE DRILL CUTTINGS. PLEASE NOTE THAT DRILL CUTTINGS FOR ONSHORE TREATMENT ARE ONLY PRODUCED FOR CERTAIN SECTIONS.

Downstream & upstream emissions from transport and treatment of drill cuttings		
	Unit	
NO_x	kg/tonne of waste	0.195
SO_x	kg/tonne of waste	0.033
GHG	kg/tonne of waste	169
$PM_{2.5}$	kg/tonne of waste	0.183
Water usage	m^3/tonne of waste	1.557

6.3 Chemicals

The chemicals[8] used on the rig consist of 46 specific tradenames. For confidentiality reasons tradenames are excluded from this report. The active ingredients in the chemicals are known to DEPA. As the ingredients in the chemicals used are confidential, color-codes are used by both the regulators, operators and service providers to categorize the offshore chemicals. The permits for use of the chemicals are based on the color coding presented in Table 6-7.

TABLE 6-7: COLOR CODING OF CHEMICALS ACCORDING TO DEPA, CORRESPONDING TO THE CODING USED BY OSPAR. THE OSPAR EVALUATION METHOD FOR OFFSHORE CHEMICALS ALSO COMPRISES CRITERIA FOR BIODEGRATION, WHICH MEANS THAT CHEMICALS CAN ONLY BE RATED YELLOW OR GREEN IF THE BIODEGRATION RATE IS HIGH.

Color coding used on the chemicals used on the rig

The color codes used by the Danish Environmental Protection Agency, DEPA, to describe the environmental hazard of offshore chemicals are in accordance with OSPAR regulation (OSPAR 10/23/1 Annex 10, www.ospar.org/work-areas/oic). The color coding is as follows:

- Black chemicals are the most critical and not acceptable within offshore discharges
- Red chemicals are environmentally hazardous to such an extent that they should generally be avoided and substituted where possible
- Yellow chemicals are those that do not fall into any of the above categories, i.e. substances exhibiting some degree of environmental hazard, which in case of significant discharges can give rise to concern.
- Green chemicals are considered not to be of environmental concern (chemical substances on OSPAR's so-called PLONOR list, i.e. a list of substances that are considered to “Pose Little Or No Risk” to the environment)

The total use of chemicals divided between the four color categories is presented in the figure below. Please note that black and red chemicals are not permitted in discharges to sea.

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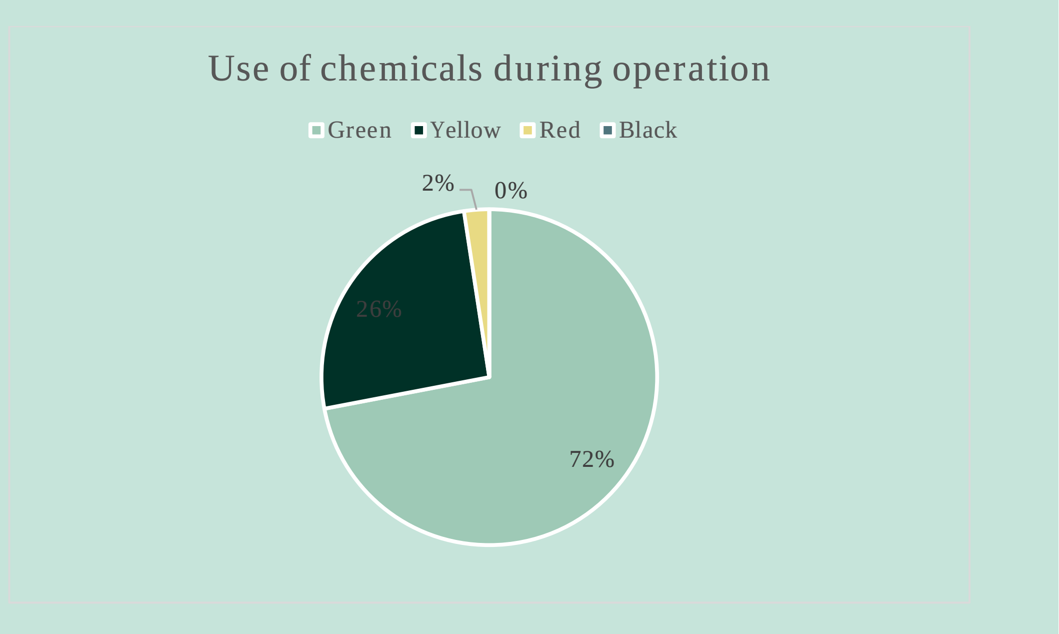
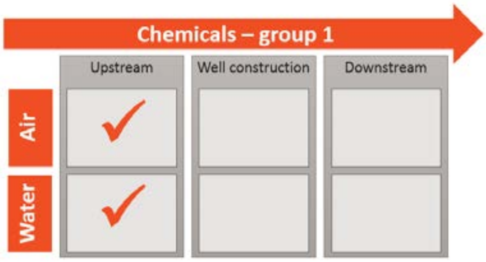
[8] Monitoring data for individual chemical input supplied by DONG



FIGUR 6-3: OVERVIEW OF THE CHEMICAL CONSUMPTION IN WELL CONSTRUCTION DIVIDED ON COLOR CODE OF CHEMICAL.

The chemicals are among others used as viscosifier, as cementing chemicals, emulsifiers, cleaning agent and others. Please refer to Appendix 2 for more information on the types of chemicals and color coding.

Confidentiality issues and the scope of the project does not allow for a full, individual analysis of all chemicals used in the well construction. Instead, chemicals are divided into two groups to capture the upstream impact and the impact during well construction and the results are used to estimate the total impact from all the used chemicals.



Group 1 chemicals were selected in order to assess the upstream impacts on the environment from the production of the chemicals and transportation of the chemicals to Esbjerg Harbour. It is assessed that the three most used (by volume) chemicals in the drilling operation are relevant indicator chemicals for assessing the upstream impacts.

Group 2 chemicals were selected in order to assess the environmental impact from permitted discharge to sea during operation. In order to achieve a conservative estimate of the impacts caused by permitted discharges, the three discharged chemicals with the highest color rating relative to used volume were selected.

The rating of the chemicals for Group 2 was performed as follows: For each chemical, information on the color coding of active ingredients in the product was examined. One yellow chemical may contain only 20 % yellow rated substances, whereas another yellow chemical may contain double the amount. Thus the latter chemical was assessed as relatively more 'yellow' – that is relatively more environmentally hazardous. Using a relative score from 1-4 through the OSPAR rating (green, yellow, red and black) and scaling by multiplying with the amount of chemical used it was possible to rank all chemicals according to usage combined with relative environmental hazardousness. The ranking allowed for estimation of the impacts for the remaining chemicals by scaling the impacts of the three chemicals in Group 2 to the rest of all chemicals.

The downstream handling of waste containing chemicals is addressed in the slop scenarios, chapter 7.1. Chemicals selected for the analysis of spills are described in chapter 7.2.

Drilling activities are divided into two phases - one using water based mud (WBM) and one using oil based mud (OBM). WBM is used in the upper sections and the OBM in the lower sections. The cuttings containing chemicals from WBM and other chemicals used when drilling with WBM can be discharged directly to sea in compliance with permits. When drilling with OBM the cuttings must not be discharged to sea directly. Cuttings containing OBM are processed in the Mudcube unit which allows the reuse of the chemicals in the OBM, whereas the cuttings with residual OBM are sent to Soil Recovery for treatment. Slop water from the OBM drilling may be sent directly for onshore treatment at Soil Recovery (scenario 1) or treated in the RENA slop unit thereby allowing processed water to be discharged to sea within existing permits whereas the retentate from the unit is sent to Soil Recovery for treatment (scenario 2). The calculations are based on these mass flows which are illustrated in the figures below.

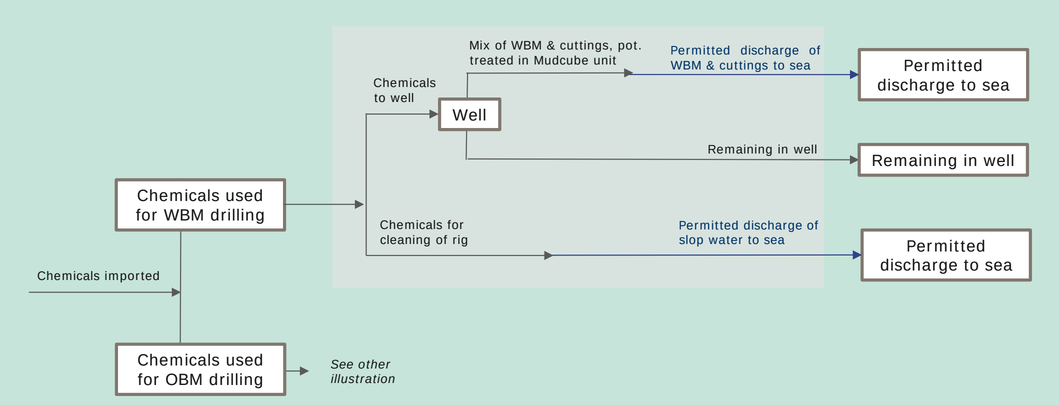


FIGURE 6-1: FLOW DIAGRAM CHEMICALS WHILE DRILLING WITH WBM

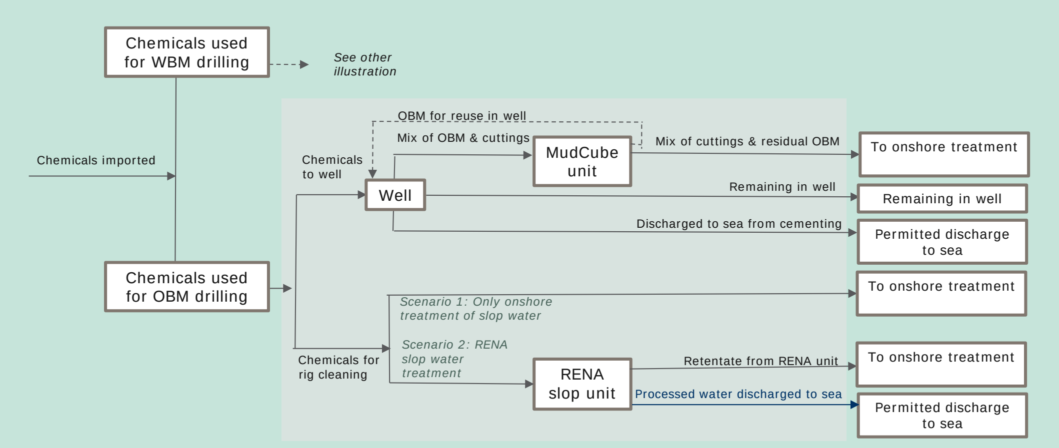


FIGURE 6-2: FLOW DIAGRAM CHEMICALS WHILE DRILLING WITH OBM

In the illustration below the total usage of chemicals divided on sections are presented. The illustration shows that the majority of the chemicals (in kg) are used in section 17½” and 12 ½/4 “.

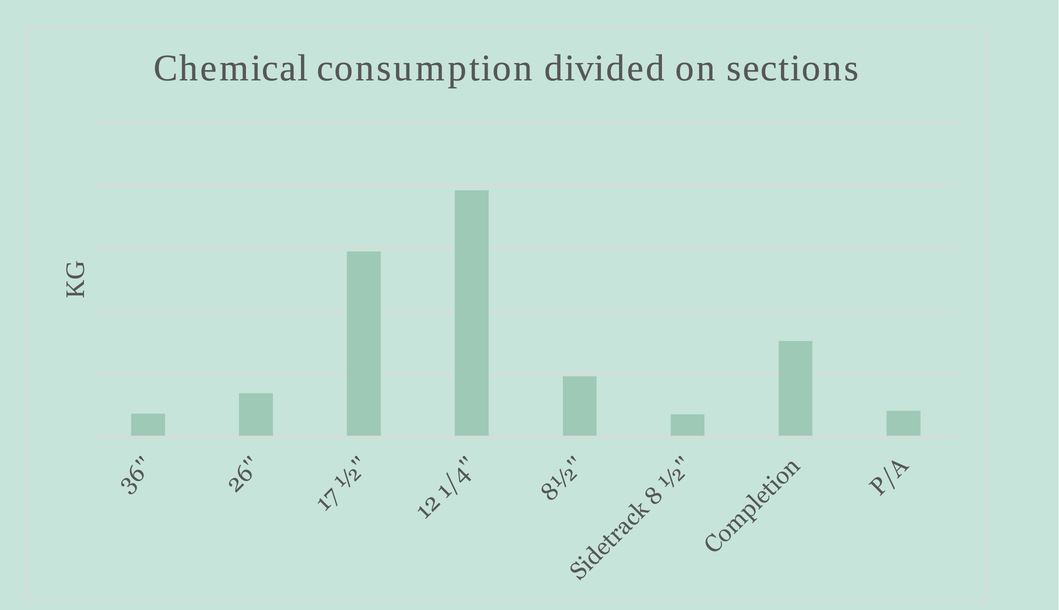


FIGURE 6-3: THE USAGE OF CHEMICALS DURING WELL CONSTRUCTION DIVIDED ON SECTIONS

6.3.1 Upstream - Chemicals Group 1

The production of chemicals and transportation of chemicals from production site to Esbjerg Harbour causes emissions and impacts on the environment, in relation to our scope, through emissions to air and water.

Environmental impacts were assessed using individual LCA analysis[9] for three group 1 chemicals.

In the table below the upstream emissions calculated in the LCA are presented.

TABLE 6-8: UPSTREAM EMISSION FACTORS FOR THE THREE CHEMICALS ANALYSED BASED ON LCA

Chemical		Chemical 1	Chemical 2	Chemical 3
GHG	kg/tonne chemical	183	900	986
NO_x	kg/tonne chemical	0.163	0.701	1.63
SO_x	kg/tonne chemical	0.779	2.15	9.7
$PM_{2.5}$	kg/tonne chemical	0.16	0.39	1.62
Water usage	m^3/kg chemical	1.33	0.00039	2.6

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[9] Individual LCA analysis of the three most used chemicals during the well construction, COWI

Please refer to Appendix 4 for description of the LCA approach. The chemicals are produced in Europe and it is assumed that raw materials for the production also origin from Europe. It is seen from the table that the upstream emissions from the 3 chemicals are very different.

The LCA results for these 3 chemicals were used to estimate the upstream impacts for each of the remaining chemicals in the following way: The impacts of a specific chemical used on the rig was estimated using the weighted average of the 3 group 1 chemicals multiplied with the actual volume used of the specific chemical. In this way the upstream impacts of all chemicals used was included in the final results.

TABLE 6-9: UPSTREAM EMISSIONS FROM PRODUCTION AND TRANSPORTATION OF CHEMICALS TO ESBJERG HARBOUR. EMISSIONS COVER ALL CHEMICALS IMPORTED TO THE RIG, AS THE LCA DATA FOR THE THREE GROUP 1 CHEMICALS WERE USED FOR SCALING. SEE TEXT FOR FURTHER EXPLANATION. THE EMISSIONS ARE GIVEN AS % OF UPSTREAM EMISSIONS.

Emission					
	Unit	Raw material	Transportation	Production of input	Transportation
NO_x	%	67	1	2	30
SO_x	%	90	0	3	7
GHG	%	70	1	2	27
$PM_{2.5}$	%	86	0	3	11
Water usage	%	96	1	2	1

No specific data was found on the water efficiency on chemicals plants. It is assumed that the upstream water discharge is equal to 50 % of the water usage thus allowing for water embedded in the products and for optimisation of water efficiency on the actual chemical plants.

6.3.2 Well construction – Group 2 chemicals

In order to estimate the societal cost from permitted discharges of chemicals, the three most environmentally hazardous chemicals were selected using the previously mentioned rating system.

Permitted discharges of chemicals to the sea[10] during well construction account for 337,645 kg. The chemicals discharged are either green or yellow chemicals as no red or black chemicals nor oil are discharged from the rig. Please note that the tables describe the total volume of chemicals discharged and that each permitted discharge may be of various sizes. The impact on the environment and the dependency of the discharge volume are addressed in the following section.

Please note that impacts following usage of group 1 chemicals during well construction are set to zero, as they are handled through scaling of the results found for group 2 chemicals.

The environmental impacts from the permitted discharges to sea are assessed by estimating the physical surface water area negatively affected.

The method applied is based on the "PEC/PNEC" model[11](see Appendix 3) that calculates the ratio between the Predicted Environmental Concentration (PEC) of a specific chemical substance in the

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[10] Monitoring data for individual chemical input supplied by DONG

[11] "PEC/PNEC" model calculations COWI

environment and the Predicted No Effect Concentration (PNEC), at which marine organisms are at no risk of being negatively affected. The distance where PEC/PNEC = 1 is the distance beyond which the risk is considered negligible ("no risk").

The PEC values are determined based on actual discharge quantifications and the oceanographic processes determining the dilution, drift and spreading. The basic theory behind these processes is described in terms of Gaussian dilution processes. The PNEC values are based on eco-toxicological laboratory tests for each substance.

All three group 2 chemicals selected for the assessment contain only one active chemical substance, the rest is water. Therefore no additive effects have been taken into account.

As a conservative approach, it is assumed the evaporation of chemicals is negligible and therefore set to zero. The following oceanographic assumptions are taken for conducting the PEC/PNEC calculations: Current velocity: 0.05 m/s (middle water depth) and water depth: 70 m. No degradation of the substance is included in order to make a conservative estimation of the affected area and volume.

The PEC values for the permitted discharge of the three Group 2 chemicals are presented in Appendix 3. The average distance affected is 120 m, with a standard deviation of 103 m. The average water volume affected is 206 m^3, with a standard deviation of 285 m^3. Due to the small vertical dispersion in the ocean, the plume will be relatively horizontal ("flat"). Based on the discharge events addressed for the three Group 2 chemicals, the maximum water volume affected to a degree where a negative effect on marine organisms can be expected was approximately 800 m^3. The average area affected is 185 m^2.

The discharges of Group 2 yellow chemicals addressed in the calculations represent different volumes of discharge and different spill durations. The affected areas for each of the chemicals are used to estimate a best fit between the volume released in the discharge and the affected area. These fits are used to estimate the affected area for all other permitted discharges taking volume released and toxicity into account.

6.3.3 Downstream

Downstream impacts following the use of chemicals are addressed together with the scenarios on slop water handling and onshore treatment of waste in chapter 7.1.

7. Scenarios addressed

7.1 Slop water handling with or without offshore RENA Slop Water Treatment Unit

This actual drilling operation used conventional onshore slop water treatment prior to installation of the RENA unit. As several thousand cubic meters of slop water is produced during OBM drilling and clean-up the cost to the operator and to the environmental in terms of impacts following emissions is substantial. Alternative solutions have therefore been explored and DONG Energy have assessed and installed the RENA slop water treatment unit on the rig during drilling with OBM.

The actual set up of slop water handling is addressed as well as two other scenarios:

- **Actual set up** where the Rena unit was installed during the activity and was therefore only partly used. Thus part of the slop water was sent to shore and a proportion was treated in the RENA unit
- **Scenario 1: Conventional slop water treatment** onshore. All slop water from OBM drilling is transported to Soil Recovery A/S in Nyborg for treatment.
- **Scenario 2: RENA slop water treatment unit** of all slop water from OBM drilling. Processed water is discharged to sea in compliance with permits. Retentate – the remaining waste stream from the RENA unit - is treated onshore at Soil Recovery A/S in Nyborg

Scenarios 0, 1 and 2 are described later using the emissions presented in the following sections.

7.1.1 Emissions used in the scenarios

Emissions to air for all slop water scenarios includes emissions from

- Diesel fuel consumption for transportation of slop water from the rig to Soil Recovery including upstream emissions due to production and transport of the fuel to Esbjerg Harbour

- Electricity consumption for the treatment plant at Soil Recovery including upstream emissions to air due to production and transportation related to electricity production

Emissions to water for all scenarios includes

- Upstream water consumption from diesel and electricity production and transportation. It is assumed when there is a water consumption it will result in waste water generation and discharge

- Discharged water from the treatment plant at Soil Recovery including both the sewage water from the waste and sewage water deriving from other water usage on the plant

A density of 1.5 kg/l is assumed for the untreated slop water.

7.1.1.1 Operation of RENA unit and transportation of slop water to Soil Recovery

The emissions following the production and transportation of diesel to the rig based on LCA data and operation of the RENA unit pr. tonne of slop water are presented in the table below:

TABLE 7-1: EMISSIONS FROM FUEL CONSUMPTION FOR OPERATING THE RENA UNIT, INCLUSIVE UPSTREAM EMISSIONS FROM PRODUCTION AND TRANSPORTATION OF FUEL TO ESBJERG HARBOUR (PER UNIT SLOP WATER PRODUCED)

Emissions from production, transport and use of diesel for operating the RENA unit, pr. tonne slop water					
	Unit	Operation Rena unit	Transport sea	Transport truck	Treatment
NO_x	kg/tonne	0.031	0.87	0.009	0.010
SO_x	kg/tonne	0.002	0.24	0.001	0.002
GHG	kg/tonne	2.67	18.77	1.36	14.912
$PM_{2.5}$	kg/tonne	0.003	0.020	$2.2*10^{-4}$	0.010
Water usage	m^3/tonne	0.16	2.13	0.072	0.057

7.1.2 Actual slop water treatment

This section describes the actual set up of slop water treatment during the drilling operation. The actual slop water treatment setup is used for comparison with alternative slop water treatment solutions.

A proportion of the slop water was transported to shore for treatment, but the majority of the slop water was treated in the RENA unit. The processed water from the RENA unit was discharged to sea according to permits and the retentate from the RENA unit was transported onshore for treatment at Soil Recovery.

Data from chapter 7.1.1 were used to calculate the total emissions (upstream, operation and downstream) following the actual slop water handling. The overall impacts are summarised in the table below:

TABLE 7-2: EMISSIONS FROM THE ACTUAL SLOP WATER HANDLING (ACTUAL SETUP). ALL EMISSIONS IN THE VALUE CHAIN ARE INCLUDED, THAT IS EMISSIONS FROM UPSTREAM PRODUCTION AND TRANSPORT OF FUELS AND ENERGY USED FOR THE RENA UNIT, VESSELS, TRUCKS AND SOIL RECOVERY, AS WELL AS THE EMISSIONS FROM OPERATION OF THE RENA UNIT, VESSELS AND TRUCKS (WELL CONSTRUCTION) AND TREATMENT AT SOIL RECOVERY (DOWNSTREAM). THE EMISSIONS ARE GIVEN AS A % OF TOTAL EMISSIONS.

Section	GHG	NO_x	SO_x	$PM_{2.5}$	Water usage
Unit	%	%	%	%	%
36"	0	0	0	0	0
26"	0	0	0	0	0
17 ½"	0	0	0	0	0
12 1/4"	87	91	93	86	85
8 ½"	5	4	4	5	7
Sidetrack 8 ½"	4	3	2	4	4
Completion	4	2	1	5	4
P/A	0	0	0	0	0
Sum	100	100	100	100	100

7.1.3 Scenario 1: Conventional slop water treatment

Scenario 1 assumes that all produced slop water during OBM drilling is transported to Soil Recovery A/S in Nyborg for treatment. This is a very common/conventional treatment of slop water.

The overall impacts are summarised in the table below:

TABLE 7-3: EMISSIONS FROM SLOP WATER HANDLING IN SCENARIO 1 – CONVENTIONAL TREATMENT AT SOIL RECOVERY. ALL EMISSIONS IN THE VALUE CHAIN ARE INCLUDED, THAT IS EMISSIONS FROM UPSTREAM PRODUCTION AND TRANSPORT OF FUELS USED FOR THE VESSELS, TRUCKS AND SOIL RECOVERY, AS WELL AS THE EMISSIONS FROM OPERATION OF VESSELS AND TRUCKS (WELL CONSTRUCTION) AND TREATMENT AT SOIL RECOVERY (DOWNSTREAM). THE EMISSIONS ARE GIVEN AS % OF TOTAL EMISSIONS.

Section	GHG	NO_x	SO_x	$PM_{2.5}$	Water usage
Unit	%	%	%	%	%
36"	0	0	0	0	0
26"	0	0	0	0	0
17 ½"	0	0	0	0	0
12 1/4"	9	9	9	9	9
8 ½"	51	51	51	51	51
Sidetrack 8 ½"	40	40	40	40	40
Completion	0	0	0	0	0
P/A	0	0	0	0	0
Sum	100	100	100	100	100

7.1.4 Scenario 2: RENA slop water treatment unit for all slop water

Scenario 2 assumes that all slop water produced during OBM drilling is treated by the offshore RENA unit. Processed water is discharged to sea in compliance with permits. Retentate – the remaining waste stream from the RENA unit - is treated onshore at Soil Recovery A/S in Nyborg. According to DONG information, the retentate amounts to approximately 0.6-0.7% of the processed slop water.

Data were used to calculate the total emissions (upstream, operation and downstream) from the actual slop water handling. The overall impacts are summarised in the table below:

TABLE 7-4: EMISSIONS FOLLOWING SLOP WATER HANDLING IN SCENARIO 2 – ALL SLOP WATER IS TREATED IN THE RENA UNIT. ALL EMISSIONS IN THE VALUE CHAIN ARE INCLUDED, THAT IS EMISSIONS FROM UPSTREAM PRODUCTION AND TRANSPORT OF FUELS AND ENERGY USED FOR THE RENA UNIT, VESSELS, TRUCKS AND SOIL RECOVERY, AS WELL AS THE EMISSIONS FROM OPERATION OF THE RENA UNIT, VESSELS AND TRUCKS (WELL CONSTRUCTION) AND TREATMENT AT SOIL RECOVERY (DOWNSTREAM). THE EMISSIONS ARE GIVEN AS % OF TOTAL EMISSIONS.

Section	GHG	NO_x	SO_x	$PM_{2.5}$	Water usage
Unit	%	%	%	%	%
36"	0	0	0	0	0
26"	0	0	0	0	0
17 ½"	0	0	0	0	0
12 1/4"	15	13	11	15	15
8 ½"	32	38	45	31	32
Sidetrack 8 ½"	27	31	37	25	26
Completion	26	18	7	29	27
P/A	0	0	0	0	0
Sum	100	100	100	100	100

7.2 Unintended discharge

Unintended discharges are included as thought experiments, i.e. hypothetical scenarios allowing for a choice of number, type and size of unintended discharges to sea during well construction. This means that the thought experiments are not based on data from the Hejre Field. The assessment method applied is similar to the method used for calculating the affected areas from permitted discharge and is described in previous chapter.

From confidential registrations of spills from drilling activities on several rigs in the North Sea it is seen that unintended discharges often consist of chemicals, diesel fuel or hydraulic oil. Crude oil is rarely seen in unintended discharges.

For the purpose of the thought experiments unintended discharge sizes of 10, 25 and 100 kg are addressed for the following types of assumed components:

- Yellow class chemical assumed similar to Chemical 1
- Red class chemical (hypothetical substance with environmental characteristics similar to red class chemicals)
- Oil (diesel)

Color classes of chemicals are described in chapter 6.3.

It is assumed that the discharges are unintended and hence occur over a relatively short period of 0.1 hour (= 6 minutes). The discharges are assumed to spread at mid water depth and the current speed is set to 0.05 m/s. This is a conservative assumption since dispersion is larger in the upper layers of the ocean.

The calculations are presented in Appendix 3 in terms of conservative estimates of the affected areas following hypothetical discharge sizes of 10 kg, 25 kg and 100 kg. Please note that an oil discharge of 100 kg equals approximately 0.08 m^3.

The results are presented in the table below. It is found that small scale unintended discharges will result in relatively large impacts whereas increasing spill volumes will increase the impact area/volume proportionately less.

TABLE 7-5: OVERVIEW OF THE ESTIMATED IMPACTED AREAS FROM A HYPOTHETICAL SPILL. DUE TO THE SIGNIFICANT VARIANCE IN THE INPUT PARAMETERS AND THE GENERAL UNCERTAINTY OF THE METHOD, THE RESULTS ARE TO BE UNDERSTOOD AS INTERVAL AND ORDERS OF MAGNITUDE. METHODOLOGY IS PRESENTED IN APPENDIX 3

Discharge volume & type	**10 kg**			**25 kg**			**100 kg**		
	Area (m^2)	Length (m)	Volume (m^3)	Area (m^2)	Length (m)	Volume (m^3)	Area (m^2)	Length (m)	Volume (m^3)
Yellow chemical	<100	<10	<1	<100	<10	<1	<100	<10	<1
Red chemical (PNEC 1-10 ug/l)	2,400-7,200	105-220	100-420	4,000-12,000	150-300	200-800	8,000-20,000	230-420	500-1,500
Oil (thickness 0,1-0,3 nm)	37,000-110,000	220-380	NA	93,000-280,000	340-600	NA	370,000-1,200,000	690-1,200	NA

For spilled oil, the impacted volume is assessed to be so small that it is denoted as "NA" in the table above, since the oil is not likely to be dissolved in water under the slick to a considerable extent.

Due to the significant variance in the input parameters and the general uncertainty of the method, the results are to be understood as interval and orders of magnitude with due respect to the assumptions used.

7.3 Flaring during testing

Emissions from flaring during well testing are included as a thought experiment, allowing for a choice of number of standard m^3 of flaring gas. Please note that the HA-1 well was not tested, thus data is based on sector data. The following emission factors are estimated to be representative for flaring during well testing.

It is assumed that emission of particular matter during flaring is similar to PM2,5 emission for natural gas: According to *Annual Danish Informative Inventory report to UNECE (Emission inventories from the base year of the protocols to year 2013*[12]*)* the PM2,5 emission for natural gas is 0,051 g PM2.5/GJ. According to *Assessment of flare strategies, techniques for reduction of flaring and associated emissions, emission factors and methods for determination of emissions from flaring* from the Norwegian Environmental Agency black carbon accounts for up to 80% of the PM[13].

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[12] *http://dce2.au.dk/pub/SR145.pdf., table 3A-4.9* gas and oil extraction industry

[13] http://www.miljodirektoratet.no/Documents/publikasjoner/M312/M312.pdf)

TABLE 7-6: EMISSIONS FACTORS USED FOR FLARING GAS DURING TEST OF WELL. EMISSIONS ARE BASED ON DATA FROM THE ANNUAL DANISH INFORMATIVE INVENTORY REPORT TO UNECE (EMISSION INVENTORIES FROM THE BASE YEAR OF THE PROTOCOLS TO YEAR 2013 HTTP://DCE2.AU.DK/PUB/SR145.PDF). ASSESSMENT OF FLARE STRATEGIES, TECHNIQUES FOR REDUCTION OF FLARING AND ASSOCIATED EMISSIONS, EMISSION FACTORS AND METHODS FOR DETERMINATION OF EMISSIONS FROM FLARING. FROM THE NORWEGIAN ENVIRONMENT AGENCY (HTTP://WWW.MILJODIREKTORATET.NO/DOCUMENTS/PUBLIKASJONER/M312/M312.PDF)

Component	Factor	Unit
CO_2	2.34	tonne/1,000 Sm^3
CH_4	0.00024	tonne/1,000 Sm^3
N_2O	0.00002	tonne/1,000 Sm^3
NO_x	0.012	tonne/1,000 Sm^3
SO_x	0.01	tonne/1,000 Sm^3
nmVOC	0.000053	tonne/1,000 Sm^3
CO	0.0015	tonne/1,000 Sm^3
$PM_{2.5}$	0.0000019	tonne/1,000 Sm^3
Black carbon	0.0000015	tonne/1,000 Sm^3

8. Overall valuation approach

In this chapter, the valuation estimates used to attach a monetary value to the emissions to air and water are presented. The input materials and consequent emissions in the value chain are described in chapter 6. Chapter 7 defines a number of scenarios which are also analyzed by using valuation estimates.

The methodology used for the NCA is based on the principles of socio economic analysis as stated in chapter 5, where the overall methodology is presented. The point of departure for the monetary valuation is the assumption that the societal value of all emissions and their impacts in the full value chain should be taken into account in the calculations of the full environmental footprint.

For each of the environmental impacts valuation estimates have been identified. The valuation estimates translate the physical terms into monetary term allowing a comparison between impacts. Please refer to Chapter 4.3.1 for the discussion on fraction of particular matter chosen and to Chapter 5.2 for description of the environmental impacts following emissions to air and water.

The valuation estimates used for this project have been carefully selected to ensure the robustness and correctness of the results. Thus the following criteria have been in focus when selecting valuation estimates:

- Published in acknowledged literature
- Recent studies
- Geographical relevant, thus national or site specific valuation estimate before global estimates
- Methodologies related to reveal preferences compared to willingness to pay estimates where possible

Valuation estimates are usually derived from surveys or data representing a smaller area, e.g Denmark. However, to capture the full impacts it is important to also include impacts following export of emissions outside the defined area, e.g. export of air emissions to Germany for example. The valuation estimates used in this project are those including impacts regardless of location.

The detailed rationale for the selection of the used valuation estimates will be described in the following sections. In general terms the valuations estimates used to assess the impacts from air emissions are based on the human health effects, the fresh water impacts are based on the avoidance cost (in other words, the cost for treatment) and the impacts on marine water are based on the willingness of society to pay to preserve the marine areas.

Valuation estimates for sensitivity testing of the results have also been collected allowing for testing the robustness of the conclusions, see Chapter 13..

8.1 Valuation estimates

In the table beneath is an overview of all the valuation estimates used in the analysis. The rows marked with bold are key estimates where the others are the sensitivity scenarios. See chapter 8.2 for more information of the sensitivity scenarios.

TABLE 8-1: VALUATION ESTIMATES USED TO ASSESS THE IMPACT FROM STEEL CONSUMPTION. ESTIMATES IN BOLD ARE THE KEY ESTIMATES, WHEREAS THE SCENARIOS ARE USED FOR SENSITIVITY TESTING OF THE RESULTS. PLEASE NOTE THAT THE TABLE IS DIVIDED INTO AIR EMISSIONS AND EMISSIONS TO WATER BODIES

Valuation estimates	Upstream , raw, steel	Upstream, prod., steel	Upstream, chemicals	Upstream, fuel	Operations	Downstream
NOx DKK/kg	**39 (R1)**	**39 (R1)**	**39 (R1)**	**119 (R9)**	**119 (R9)**	**119 (R9)**
Low scenario 1	39 (R1)	39 (R1)	39 (R1)	39 (R1)	39 (R1)	39 (R1)
High scenario 2	105 (R1)	105 (R1)	105 (R1)	105 (R1)	119 (R9)	119 (R9)
Trucost a.o. scenario	10 (R5)	10 (R5)	10 (R5)	4 (R5)	4 (R5)	4 (R5)
SO_x DKK/kg	**86 (R1)**	**86 (R1)**	**86 (R1)**	**273 (R9)**	**273 (R9)**	**273 (R9)**
Low scenario 1	86 (R1)	86 (R1)	86 (R1)	86 (R1)	86 (R1)	86 (R1)
High scenario 2	251 (R1)	251 (R1)	251 (R1)	251 (R1)	273 (R9)	273 (R9)
Trucost a.o. scenario	7 (R5)	7 (R5)	7 (R5)	11 (R5)	11 (R5)	11 (R5)
GHG DKK/kg	**0.636 (R4)**	**0.636 (R4)**	**0.636 (R4)**	**0.636 (R4)**	**0.636 (R4)**	**0.636 (R4)**
Low scenario 1	0.083 (R1)	0.083 (R1)	0.083 (R1)	0.083 (R1)	0.083 (R1)	0.083 (R1)
High scenario 2	0.273 (R1)	0.273 (R1)	0.273 (R1)	0.273 (R1)	0.636 (R4)	0.636 (R4)
Trucost a.o. scenario	0.645 (R5)	0.645 (R5)	0.645 (R5)	0.645 (R5)	0.645 (R5)	0.645 (R5)
PM DKK/kg	**202 (R1)**	**202 (R1)**	**202 (R1)**	**211 (R9)**	**211 (R9)**	**211 (R9)**
Low scenario 1	202 (R1)	202 (R1)	202 (R1)	202 (R1)	202 (R1)	202 (R1)
High scenario 2	586 (R1)	586 (R1)	586 (R1)	586 (R1)	211 (R9)	211 (R9)
Trucost a.o. scenario	94 (R5)	94 (R5)	94 (R5)	58 (R5)	58 (R5)	58 (R5)

CONTINUED ON NEXT PAGE

Valuation estimates	Upstream, raw, steel	Upstream, prod., steel	Upstream, chemicals	Upstream, fuel	Operations	Down-stream
Fresh Water DKK/m³	**35 (R2)**	**35 (R2)**	**35 (R2)**	**35 (R2)**	**-**	**35 (R2)**
Low scenario 1	0,9 (see box below)	25 (R2)	25 (R2)	25 (R2)	-	25 (R2)
High scenario 2	50 (R2)	50 (R2)	50 (R2)	50 (R2)	-	50 (R2)
Trucost a.o. scenario	35 (R2)	35 (R2)	35 (R2)	35 (R2)	-	35 (R2)
Sea water DKK/km²/-year			**-**	**-**	**7,521,994 (R6)**	**-**
Low scenario 1			-	-	7,521,994 (R6)	-
High scenario 2			-	-	15,104,648 (R10)	-
Trucost a.o. scenario			-	-	7,521,994 (R6)	-

REFERENCES:
R1: EEA COSTS OF AIR POLLUTION FROM EUROPEAN INDUSTRIAL FACILITIES 2008-2012,
R2: PRISER FOR DRIKKEVAND OG AFLEDNING AF SPILDEVAND 2014, KONKURRENCE OG FORBRUGERSTYRELSEN,
R3: DEA, FORUDSÆTNINGER FOR SAMFUNDSØKONOMISEK ANALYSER PÅ ENERGIOMRÅDET, 2014
R4: DEPARTMENT OF ENERGY & CLIMATE CHANGE, UK, 2014, VALUATION OF ENERGY USE AND GREENHOUSE GAS (GHG) EMISSIONS,
R5: METHODOLOGY REPORT FOR NOVO NORDISK'S ENVIRONMENTAL PROFIT AND LOSS ACCOUNT, 2014,
R6: VALUING CONSERVATION BENEFITS OF AN OFFSHORE MARINE PROTECTED AREA, BÖRGER ET AL. (2014),
R7: WILLINGNESS TO PAY AMONG HOUSEHOLDS TO PREVENT COASTAL RESOURCES FROM POLLUTING BY OIL SPILLS: A PILOT SURVEY, 2009, XIN LIU, KAI W. WIRTZ, ANDREAS KANNEN, DIETMAR KRAFT,
R8: AN ACCIDENTAL OIL SPILL ALONG THE BELGIAN COAST: RESULTS FROM A CV STUDY, KARL VAN BIERVLIET, DIRK LE ROY AND PAULO A.L.D. NUNES, 2006,
R9: FROM THE MINISTRY OF ENVIRONMENT. MILJØ- OG FØDEVAREMINISTERIETS MILJØØKONOMISKE NØGLETALSKATALOG, 2015,
R10: TWENTY THOUSAND STERLING UNDER THE SEA: ESTIMATING THE VALUE OF PROTECTING DEEP-SEA BIODIVERSITY

As the framework conditions are very different in China where the iron ore is mined (in this terminology, upstream raw steel) an alternative approach to evaluating the water usage has been applied in scenario 1. In the box beneath it an explanation is provided of how the alternative price on water has been assessed.

TEXT BOX 8-1: ALTERNATIVE VALUATION OF THE IRON ORE MINING

The resource scarcity value of water can be exemplified by the use of water in irrigated agriculture If water is used for mining it will (not considering effects from pollution) not be available for irrigated agriculture, which would typical be the water using economic activity displaced by other uses of water.

The economic value that can be created by water in irrigated agriculture can be roughly calculated by looking at the use of 1 hectare of land. One hectare of land in industrialized countries can typically* produce 2 tonnes of cotton using 15,000 m^3 water. The cotton can be sold on the international market for around 800 USD/tonne, i.e. a total of 1,600 USD/ha. If the water was used for irrigated cotton production, it would (not considering other production costs or land rents) produce cotton worth 0.1 USD/m^3 water or 0.6 DKK/m^3.

An alternative irrigated agricultural crop which could be displaced by use of water for mining could be wheat. Examples for wheat yield and water use could be 4 tonne/ha and 6,000 m^3/ha water use. With a crop price of 300 USD/tonne of wheat, the value of water would be 1,200 USD/6000 m3 equal to 0.2 USD/m^3 or 1.2 DKK/m^3.

As an average that gives a value of 0.9 DKK/m^3.

*Note: Yields and water usages can vary a lot depending on weather, soil conditions, geographical location and agricultural practices. The numbers mentioned above are purely illustrative.

Where necessary, due to the age or origin of the study, the valuation estimates have been adjusted. A consumer price index has been used to ensure that all prices are in 2014-prices. If the valuation estimates are based on foreign studies these have been adjusted regarding differences in number of household, currency and income level.

It has been chosen not to adjust the valuation estimates due to the geographical location of the well. This is done based on the conclusions in the report *Ship emission and air pollution in Denmark* (DEPA, 2009) and *Renere skibsfart* (Det økologiske råd, 2011), where a similar approach have been applied for ship transport in marine waters. This could lead to a slight overestimation of the impacts.

8.1.1 Steel

As described in chapter 6 only the upstream emission and belonging environmental impacts will be included in the analysis.

8.1.1.1 Upstream

Valuation estimates are presented in Table 8-1. The following assumptions are used with respect to upstream impacts from steel production and transportation to Esbjerg Harbour:

The valuation estimates of air emission of NO_X, SO_X and PM from mining, producing and transporting the steel to Esbjerg Harbour are based on estimates from EEA. The EEA estimates are valid for environmental impacts from air emissions in EU. The same estimates are also used for air emissions outside EU, e.g. for emissions related to mining in China. This assumption is based on the fact that the valuation estimates for NO_X, SO_X and PM emissions are based on human health impacts and are directly linked to the population density. There is no indication that production of steel and the mining of ore takes place in less populated areas than the EU average population density.

Valuation of impacts from GHG emissions from mining, production and transport of steel are assessed using the European quota price projections from EEA. GHG poses a global impact why the same price applies at all geographical locations.

Upstream impacts from emissions and discharges to water (expressed as upstream emissions to water (UEW) are assumed as proportional with the water consumption in the mining and production activities. The water consumption is estimated in the LCAs. The impact on the water resources will occur through both effects on the availability and quality of water resources due to extraction and/or depletion of the water resource and through impacts on the water resources due to discharge of untreated or treated waste water generated from the production and mining processes. The usage of water in the production of steel is assumed as equal to the amount of waste water that is discharged from the upstream activities. This is considered a conservative assumption as it does not include water efficiency schemes or internal treatment reducing the cost to society. It is furthermore assumed that the generated wastewater from production requires treatment afterwards. The externalities of the water emissions are here assumed to be equal to the cost of having the water treated together with the green taxes paid related to waste water treatment: More explicit by using the principle of cost recovery from the EU Water Framework Directive the valuation estimate is based on the cost of wastewater treatment. In addition when paying for water treatment, the consumer pays "green" taxes. These taxes are assumed to be equal the cost of externalities related to the impacts the wastewater causes to the environment.

The valuation estimates are thus assumed to be the sum of the cost of treatment and the green taxes. The green taxes are in Denmark introduced to account for the externalities. These are assumed to be the same across Europe as the waste water treatment costs do not vary much[14] and are furthermore assumed to be usable and a conservative estimate for water impacts outside the EU as well, e.g. when mining in China, where the iron ore for the steel is sourced. China is selected as much of the iron ore originates from there and it is assumed that it is the marginal source. In other words if there are changes in the supply and demand in the world market for iron ore then Chinese mining activities will directly react.

8.1.2 Fuel and electricity

8.1.2.1 Upstream

The upstream valuation estimates and the estimates to be used in sensitivity testing of the results are presented in Table 8-1 . The assessment of the fuel production distinguishes itself from the chemical and steel production by taking place in Denmark thus Danish valuation estimates have been used.

Valuation of impacts from air emissions during production and transportation of fuels and electricity are based on estimated emissions of NO_x, SO_X and PM from LCAs combined with consolidated valuation estimates from the Danish Ministries.

Valuation of upstream impacts from emission of GHG from production and transportation of fuel and electricity are assessed using EU projections of the quota prices similar to the approach used for steel, chapter 8.1.1.1.

Valuation of upstream impacts on water bodies (UEW) are assessed based on the water consumption from the production of fuel and electricity, which are estimated in the LCA. At the oil pipe station in Esbjerg and at the refinery the sewage water production is at same level or higher than the water usage. On the other hand the sewage water production during other part of the upstream value chain is lower than the water consumption. As an averaged and still conservative approach it is therefore assumed that the generated wastewater upstream equals the water consumption. Please refer to argumentation in chapter 8.1.1.1.

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[14] VEWA, Vergleich Europäischer Waseer- und Adwasserpreise, 2015

8.1.2.2 Well construction

Valuation of impacts from air emissions during well construction is based on the actual emissions of NO_x, SO_X and PM together with consolidated valuation estimates from Danish Ministries. The valuation estimates and estimates to be used in sensitivity testing of the results are found in Table 8-1.

As discharged oil components are in compliance with permits it is assumed that the environmental impacts are negligible, thus the cost to society is set to zero. Fuel spills are addressed in chapter 7.2 and 8.1.5.

8.1.2.3 Downstream

Valuation of impacts from air emissions from transport and treatment of the mud, cuttings and retentate are also assessed using the consolidated valuation estimates from Danish Ministries. The valuation estimates and estimates to be used in sensitivity testing of the results are presented in Table 8-1.

Fuel spills during transportation of waste and treatment of waste is assumed negligible and therefore set to zero. Valuation of fuel spills to sea during transportation of waste is addressed in chapter 7.2 and 8.1.5.

8.1.3 Chemicals

Chemicals are as describe in chapter 6 analyzed by looking at two groups of chemicals - one for upstream and one for operation and downstream.

8.1.3.1 Upstream

Air emissions according to scope are assessed through the LCAs for the production and transportation of chemicals from sites in Europe. The valuation is based on valuation estimates from EEA, as these describe the impact in the European countries.

Impacts from emissions of GHG from production and transport of chemicals are assessed using the European quota price projections.

Valuation of impacts from discharges to water bodies (UEW) is determined based on the water consumption from the production of chemicals similar to the approach used for steel and fuels.

8.1.3.2 Well construction

The valuation of the societal cost from permitted discharge of chemicals to the marine environment during the drilling operation is based on the "PEC/PNEC" model presented in the previous section. Thus the 'unit' relevant to the valuation is the area in m^2 affected negatively from the discharge.

Several studies on valuation of impacts in the marine environment have been studied. The most usable valuation study is assessed to be the valuation study of Dogger Bank in the Southern North Sea: *Valuing conservation benefits of an offshore marine protected area,* Börger et al. (2014). The estimates are included in Table 8-1.

The cited study is a UK research project estimating the value of marine protected areas in the North Sea. The valuation is based on a stated preference study using the choice experience methodology. The area valuated in the study is the Dogger Bank, located close to the Hejre Field. The value estimated is for a marine protected area, where activities are restricted to cause minimum impact on the environment. As in this case the PEC/PNEC model provides an area that is negatively affected by the discharges and therefore it is assumed that the valuation study will be applicable to this situation. The marine protected area addressed in the UK study is a part of the Dogger Bank with an area 17,600 km^2. As the study is from UK, the valuation estimates are adjusted according to the number of households and the income level in Denmark.

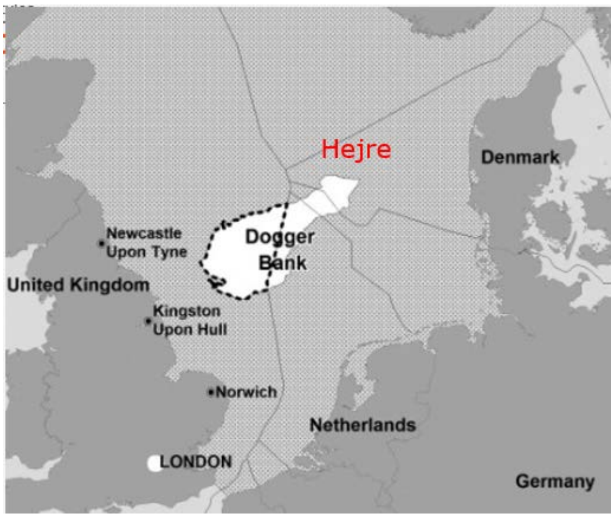

FIGURE 8-1: VALUATION STUDY ON PART OF DOGGER BANK IN THE NORTH SEA, CLOSE TO THE HEJRE FIELD AND THE DRILLING RIG

In Table 8.2the valuation estimates used are presented. Other than the UK study valuation estimate from the study *Twenty Thousand Sterling Under the Sea: Estimating the value of protecting deep-sea biodiversity* is chosen for the sensitivity testing of the results. This study addresses value of the marine environment which is hidden under the surface and therefore not visual to the public.

8.1.4 Slop unit scenario 1 & 2

The valuation of the environmental impact of having - or not having - the RENA Slop Water Treatment unit installed is assessed with valuation estimates for air emission and for the water consumption in Denmark similar to the approach used in chapter 8.1.1.1 and 8.1.2.2.

8.1.5 Unintended discharges

The valuation estimates for the yellow and red chemical in spills are the same as used for valuation of impacts from permitted discharge of chemicals, see chapter 6.3.3 and the table below.

The valuation of unintended discharge of oil is based on two studies assessing the willingness to pay for avoiding oil spill. The valuation estimates are given in

Table 8-2. A study assessing the willingness to pay for more for marine protection is used for sensitivity testing.

TABLE 8-2: VALUATION ESTIMATES USED FOR UNINTENDED DISCHARGE

Unit	Key figure	Scenario 1	Scenario 2
DKK/km²/year	7,521,994 (R6)		
DKK/year		61,706,654,767 (R11)	
DKK/one off			225,075,364,162 (R12)

R6 VALUING CONSERVATION BENEFITS OF AN OFFSHORE MARINE PROTECTED AREA, BÖRGER ET AL. (2014) R11 WILLINGNESS TO PAY AMONG HOUSEHOLDS TO PREVENT COASTAL RESOURCES FROM POLLUTING BY OIL SPILLS: A PILOT SURVEY, 2009, XIN LIU, KAI W. WIRTZ, ANDREAS KANNEN, DIETMAR KRAFT, R12 AN ACCIDENTAL OIL SPILL ALONG THE BELGIAN COAST: RESULTS FROM A CV STUDY, KARL VAN BIERVLIET, DIRK LE ROY AND PAULO A.L.D. NUNES, 2006,

The two surveys proposed, used for sensitivity testing of the unintended discharge[1] results estimate the willingness to pay to avoid marine oil spills. When adjusted to numbers of inhabitants and income level the cost estimates are approximately 61 BDKK pr. year and 225 BDKK one off. Basically all three valuation estimates indicate a very high willingness in the society to pay to avoid marine oil spills. The difference between the three estimated costs indicate that environmental valuation estimates for unintended discharges are associated with some uncertainty and conclusions should be indicative.

8.1.6 Valuation - Flaring

The emission to air from flaring while testing the well will be valued as for all other air emissions during operation, see Table 8.1.

8.2 Sensitivity analysis

Table 8-1 and

Table 8-2 present both the key valuation estimates and the estimates used for sensitivity analysis. A total of three sensitivity scenarios are identified for each of the primary valuation estimates. The sensitivity scenarios are designed in order to address both lower and higher estimates, as long as they are considered relevant and from acknowledged sources.

8.2.1 Air emissions

As an example, the sources used for the sensitivity assessments for air emissions are data from

- European Energy Agency EEA - Costs of air pollution from European industrial facilities 2008-2012
- Trucost's valuation estimates presented in the Novo Nordisk's environmental profit and loss account, 2014

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[1] Willingness to pay among households to prevent coastal resources
from polluting by oil spills: A pilot survey, 2009, Xin Liu, Kai W. Wirtz, Andreas Kannen, Dietmar Kraft
An Accidental Oil Spill Along the Belgian Coast: Results from a CV Study, Karl van Biervliet, Dirk Le Roy and Paulo A.L.D. Nunes, 2006

- Non-published publication from the Ministry of Environment. Estimates carried out by DCE and report prepared by COWI

The alternative valuation estimates for the sensitivity scenarios are chosen in such a way that

- Scenario 1's are characterized by **low estimates** mainly based on EEA estimates using VOLY[15]. The aim of this scenario is to illustrate how the results would be influenced by using the lowest valuation estimates available in acknowledged literature.
- Scenario 2's are characterized by **high estimates** mainly based on EEA estimates using VSL[16] The aim of this scenario is to illustrate how the results would be influenced by using more very conservative estimates.
- Scenario 3's are characterized by mostly **Trucost**'s estimates from the Novo Nordisk EP&L where estimates are available and relevant, supplemented with estimates from other references. imates where key figures are available. The aim of this scenario is to compare the results with valuation estimates used by Trucost, as Trucost preforms many NCAs and EP&Ls. Abbreviated as 'Trucost a.o.'

As can be seen in table 8-1 the set of valuation estimates are supplemented with other sources of estimates if none were available for the specific need. E.g. the valuation for water is as described approached differently than e.g. emissions to air.

The effect of various valuation estimates is illustrated in : sets of valuation estimates are used on the actual emissions to air and the results are indexed to visualize how each sets of valuation estimates affect the overall environmental costs of the given type of emission. This shows that it is mainly the valuation of GHG that causes the (relatively) largest differences. Therefore it is concluded that the sensitivity scenarios will mainly be influenced by the choice of GHG valuation estimates. How this influences the NCA results is illustrated in chapter 13.

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[15] VOLY is value of life year

[16] VSL value of statistical life

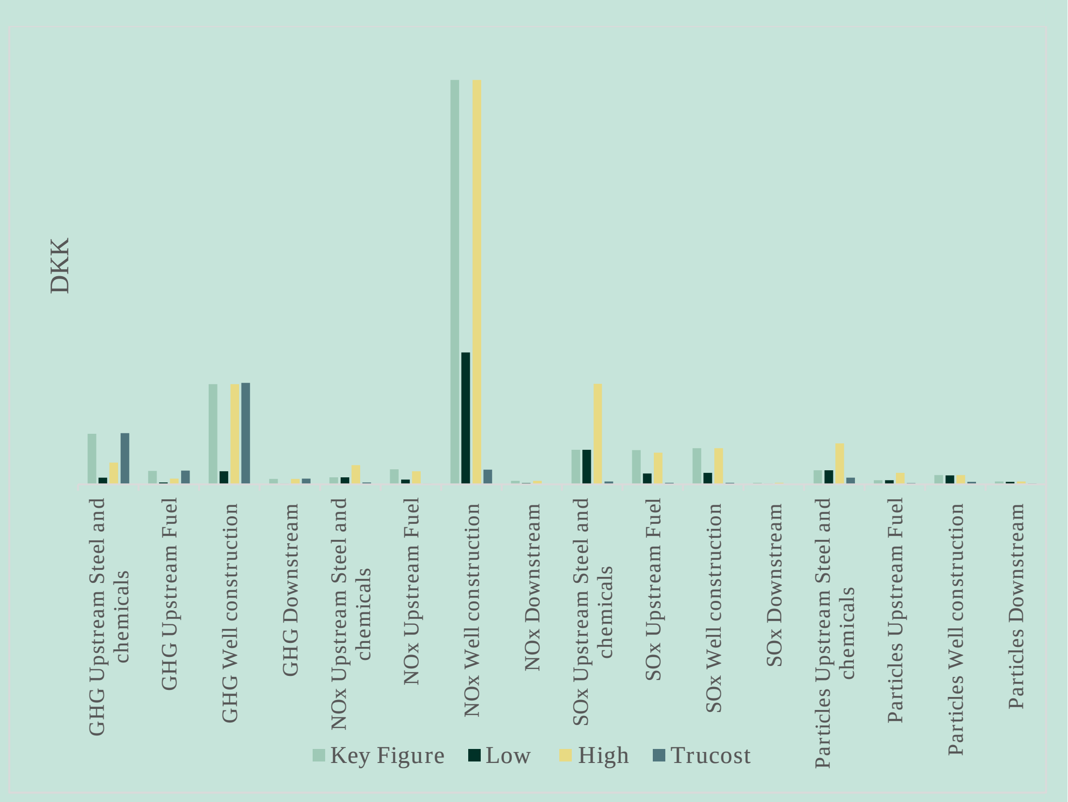

FIGURE 8-2: OVERVIEW OF THE RELATIVE EFFECT OF DIFFERENT SETS OF THE VALUATION ESTIMATES FOR AIR EMISSIONS. SEE TEXT FOR MORE EXPLANATION

8.2.2 Discharges to water bodies

The sources used for the sensitivity assessments for emissions to water bodies are:

- Valuing conservation benefits of an offshore marine protected area, Börger et al. (2014)
- Priser for drikkevand og afledning af spildevand 2014, Konkurrence- og forbrugerstyrelsen (Danish water prices)

The alternative valuation estimates for the sensitivity scenarios are chosen in such a way that

- Scenario 1's are characterised by **low estimates** – the price for waste water treatment is low. The price for impact on marine water is keep the same
- Scenario 2's are characterised by **high estimates** - the price for waste water treatment is high. The price for impact on marine water is high based on a valuation study with a higher price estimate
- Scenario 3 is that same as baseline, that is **key estimates**

The major differences in the three scenarios are in the low price for fresh water in the raw material production of ore for steel, whereas mentioned the water can be used for different purposes such as irrigation in agriculture if not used for mining.

9. Database, tool & interface

As stated, the project objective is to provide data that can inform or qualify decision making in Maersk Drilling and DONG. Activities to fulfil the objective are threefold: first a database was developed to structure the compiled data. Secondly a calculation tool was developed to calculate the impacts across tiers, emission types and input materials. Thirdly an interface was developed to allow testing of the changes in environmental cost following changes in the set-up of the well in terms of section lengths, numbers of unintended discharges and volume of flaring. The activities and the resulting building blocks developed are described below. The different building blocks are illustrated in Figure 5-1.

9.1 The database

The database is developed in excel and contains data and information on the drilling operation of the Hejre Field. The database includes both monitoring data from MD and DONG as well as LCA-data describing the environmental impacts in the upstream production of the input materials imported to the rig. The database also includes data on the RENA unit compared to conventional solutions for handling waste produced while drilling with OBM and it includes operational data from Soil Recovery A/S. All data is organized according to data and time and process data such as up- and downtime is included. The data series therefore provide a replica of the actual emissions from the well construction and the data is used to estimate the impact across different parameters such as diameter of well, types of drilling mud used etc.

In many cases both DONG and MD monitor the same type of data for their quality assurance and reporting, e.g. to the authorities. Only few data gaps e.g. missing data on specific days, where found. In case of a data gap, the data where sought in the data series received from both DONG and MD. If the missing data was not found the data gap was covered by using average data for the specific period. Many of the data included in the database are under confidentiality restrictions either from suppliers or from MD or DONG and will not be shared with the public. The intention is to disclose as much data as possible in this report, but due to confidentially issues some data and results are indexed in this report. The database also includes information related to the thought experiments on unintended discharges and flaring during well testing.

9.2 Calculation tool and Overview

A calculation tool was developed for converting all the physical data into impact on the environment in monetary terms. The tool allows for calculating the monetary cost from the chosen set up of a well using the unit cost pr. meter of a given section according to the actual drilling operation. The tool allows for comparison between different types of impacts, as well as different part of the value chain and activities, and how much each of them contributes in average pr. hour, meter of section 36" and similar.

9.3 User interface tool for testing new set ups of the well

A user interface tool was designed for testing new setup of the well construction than the actual setup of the Ha-1 well. The user interface tool allows for a choice of design of the well in terms of lengths of different diameters and others parameters. It also allows for a choice of a number of unintended discharges and a choice of flaring during testing.

The user interface tool is using data from the actual setup and thus assumes that the actual data are relevant and usable for new setups. The tool allows for comparison of the new set up with the actual setup of the well to fully understand the design options usable for optimizing the environmental footprint in the value chain. The user interface was tested by MD and DONG in order to assess the relevance of such tools for business decision making. The major findings in the usability test are presented in chapter 15.

10. Presentation of overall results

The data and valuation estimates presented in the previous chapters are used to calculate the environmental cost from the actual operation. The cost-estimates are across the value chain, the type of inputs as well as across different emissions types.

In the following chapters the results of the calculations are presented. The total cost in terms of DKK is not presented, but instead the division of costs is presented for a variety of aspects. Please keep in mind that the objective of this pilot project was to allow comparison of environmental costs across different types of emissions and parts of the value chain to demonstrate how this may support operational and strategic decision making in the business. It should also be kept in mind that the accuracy of the cost estimates depends on the preciseness of the inventory used as basis (LCA data, sector data or monitory data for the actual operation or company) and the valuation estimates used. The sensitivity analysis will address the effects of preciseness in inventory and variation in valuation estimates.

TABLE 10-1 THE FOLLOWING ABBREVIATIONS ARE USED IN THE ILLUSTRATIONS

- Tiers: Upstream (U), Well Construction (WC, including transport of materials and personnel by vessel or helicopter between Esbjerg Harbour and the rig) and Downstream (D). The activity ‘Raw materials’ in upstream tier is understood as ‘Extraction of raw materials’.
- Impacts following different types of emissions to air or emissions/discharges water e.g. in combination with the tier (e.g. U&DEW, up- & downstream emissions to water):
  - Emissions/discharge to water bodies (EW)
  - Impacts from emissions of greenhouse gasses to air (GHG)
  - Impacts from emissions of NO_X to air (NO_X)
  - Impacts from emissions of SO_X to air (SO_X)
  - Impacts from emission of particles to air ($PM_{2.5}$)

10.1 Data quality and transparency

As stated the objective of the project was to demonstrate an NCA approach focusing on selected specific types of activities and impacts and use the data and results to demonstrate the business value of using NCA data and tools. It was therefore a conscious choice to delimitate the scope and at the same time ensure a high data quality and transparency in order to use the results to address the environmental cost of not only the upstream and operational footprints but also the downstream parts of the value chain. This was achieved by using primarily site specific data and secondary company data from other sites, sector data or LCAs trying to avoid data sources that are known to provide generic or averaged data, such as e.g. Environmental extended input output data (EEIO-data).

Generally the data used for the calculation is based on best available data: the majority of the data is monitory data from the rig provided by either MD or DONG. Secondly data are retrieved from yearly environmental reports from the actual service providers used (e.g. Soil Recovery and Shell refinery) or specifications from actual technologies (e.g. the RENA Slop Unit). For those data not available through these sources, LCA assessments have been used. No data from Environmental extended input/output tables have been used in the inventory.

For well construction the monitoring data was collected on a real-time-basis thereby providing sufficient preciseness to use the data for detailed analysis, e.g. on environmental cost pr. section, pr. meter, pr. technology, pr. drilling hour etc. This allows for assessing the choice of e.g. slop water handling and also allowed fassessment of the reasons for differences in cost pr. section. The high proportion of data from direct sources results in a more accurate inventory and thus a more accurate environmental cost estimate. This qualifies the use of the data for operational and strategic decision making and also allows for a later reuse of the data to monitor improvements or for extracting data to assess benefits of other technologies.

The valuation estimates used in the project have been carefully selected to ensure the robustness and correctness of the results. In the actual case the key valuation estimates are recent and all from acknowledged literature or institutions, such as the Danish ministries and EU agencies. As sensitivity scenarios other sources of valuation estimates have been included, and also here primarily data from official bodies have been used (e.g. as EEAs estimates using other valuation approaches on value of life, see chapter 8.2) combined with estimates from Trucost a.o.

As illustrated in chapter 8.2, the valuation estimates from Trucost a.o. differ significantly from the other valuation estimates used, particularly for GHG, see also chapter 13.2. This highlights that the choice of valuation estimate is key in assessing the environmental cost associated with the value chain. Choice of valuation estimate thereby becomes key for comparing, for example, products or services from two companies. This points to the need for more specific and agency accepted valuation estimates.

Comparison of e.g. products or services from two companies also requires that the accounting methodology is comparable. Currently the NCA is not a standardised methodology and even if there was a recognised, common approach there would still be many company and site specific choices to be taken when assessing emissions, impacts and cost. This highlights the need for a high degree of transparency in the NCA approach used.

10.2 Environmental cost divided on types of emission

In the figures below the environmental costs for the full value chain are presented.

Figure 10-1 and Figure 10-2 illustrates that the majority of the footprint in the full value chain is associated with upstream discharges to water and emissions of NO_x during well construction (includes emissions from transportation of materials and personnel from Esbjerg Harbour to the rig). The impact on water resources includes both effects on the availability and quality of water resources due to extraction and/or depletion of the water resource and through impacts on the water resources due to discharge of untreated or treated waste water generated from the production.

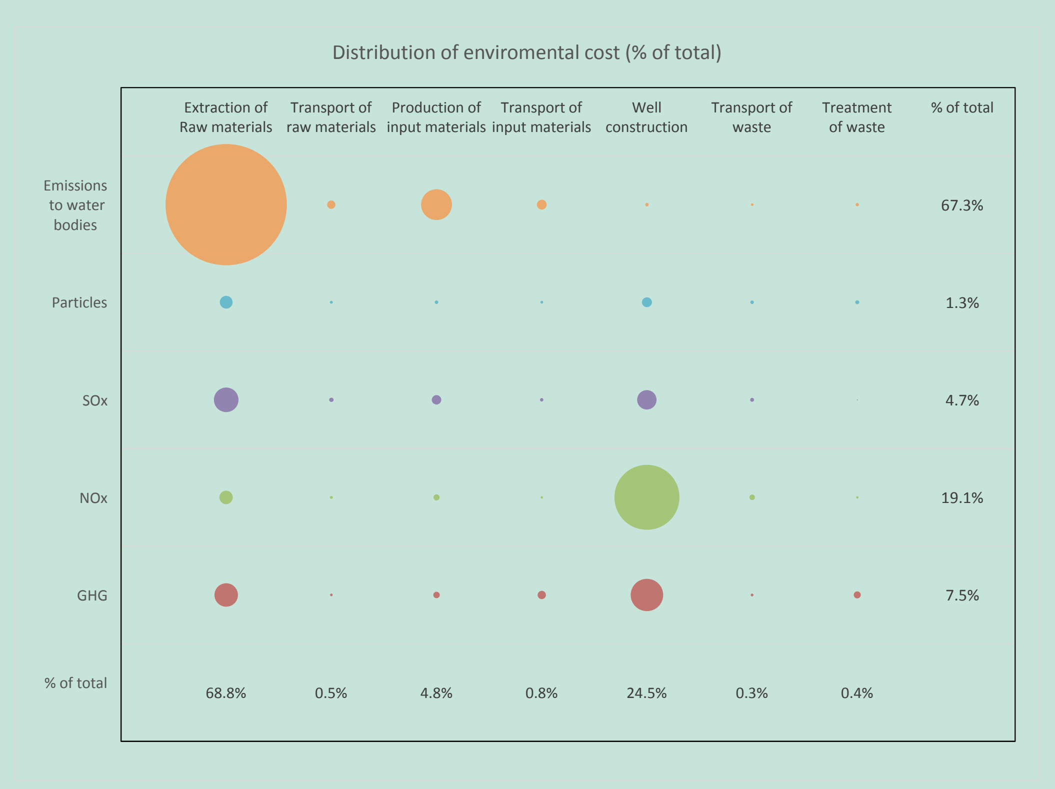

FIGURE 10-1: DISTRIBUTION OF THE TOTAL ENVIRONMENTAL COSTS IN THE VALUE CHAIN DIVIDED BY TYPES OF EMISSIONS. UPSTREAM EMISSIONS TO WATER BODIES ASSUME THAT WATER DISCHARGE EQUALS 50% OF THE WATER USAGE FOR STEEL AND CHEMICAL PRODUCTION AND 100% FOR FUEL PRODUCTION. PLEASE NOTE THAT TIER 'WELL CONSTRUCTION' INCLUDES EMISSIONS FROM OPERATION OF RIG AND OPERATION OF VESSELS AND HELICOPTERS FOR TRANSPORT OF MATERIALS AND PERSONNEL, WHEREAS EMISSIONS FROM PRODUCTION AND TRANSPORT OF FUELS FOR OPERATING THE VESSELS, RIG AND HELICOPTERS ARE INCLUDED IN 'UPSTREAM' TIERS . A SIMILAR APPROACH APPLIES FOR OTHER INPUT MATERIALS AND DOWNSTREAM ACTIVITITES.

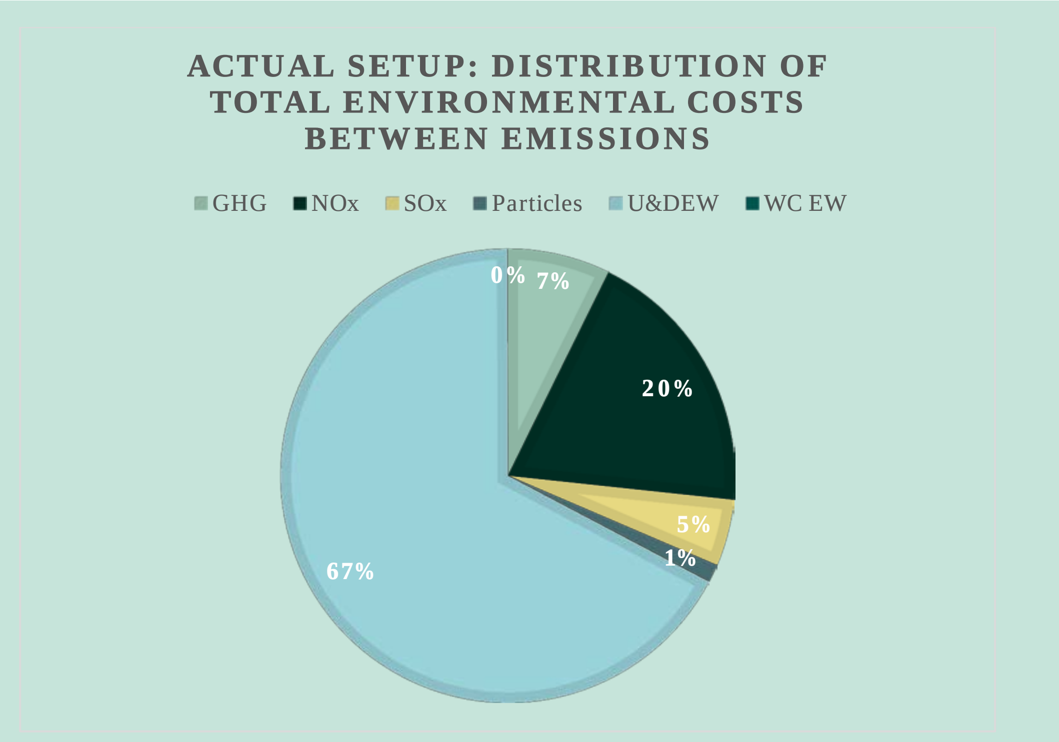

FIGURE 10-2: DISTRIBUTION OF THE TOTAL ENVIRONMENTAL COST IN THE VALUE CHAIN DIVIDED BY EMISSIONS TYPES. UPSTREAM EMISSIONS TO WATER BODIES ASSUME THAT WATER DISCHARGE EQUALS 50% OF THE WATER USAGE FOR STEEL AND CHEMICAL PRODUCTION AND 100% FOR FUEL PRODUCTION.

The reasons for a relatively high share of environmental cost associated with upstream discharges to water and the dependency of material usage are investigated further in chapter 10.4.

The emission of particles and SO_X only account for a very small share of the total. The sum of PM, SO_X, GHG and permitted discharges to sea during well construction only account for 13% of the total, see Figure 10-2.

In particularly, the share of NO_X can be attributed to the high NO_X emission during well construction. This will be further elaborated when the results for the sections are presented.

It is notable that the environmental cost associated with permitted discharges to sea during the well construction (WC EW) practically isn't visible in the illustration. Please note that some of the up- and downstream discharges to water may be discharges to sea, but as upstream data is highly based on LCA and thus not site specific, it is not possible to assess the division between discharges to fresh water bodies and discharges to sea. Thus the relative share of emissions to sea should be seen in this light. On the other hand the illustration shows that the cost of the emissions to sea related to the specific well construction is very small compared to other impacts.

The following chapters covers more about the relative size of the costs and how this may be used in operational and strategic decision making.

10.3 Using NCA data for prioritizing emissions and mitigation

From Figure 10-1 and Figure 10-2 in the previous chapters it is seen that the environmental cost related to permitted discharges of chemicals to sea during the well construction is relatively small compared to other environmental cost.

This furthermore is emphasised by the fact that the estimation of the affected area from permitted discharge of chemicals to sea during well construction is based on very conservative assumptions. It does not include weathering and other biological and physical degradation of the chemicals (also see chapter 14.1, where the effects of spatial and temporal reduction factors on unintended discharges are discussed). Please note that the OSPAR evaluation method used for the color coding of off shore chemicals also comprises criteria for biodegradation and that a biodegradable chemical can only be yellow or green if the biodegradation rate is high. Furthermore it is assumed that the area around the well represents a societal value similar to the Dogger Bank area. This again shows that the assumptions used are conservative as it assumes that the full plume reaches and affect a sensitive area.

Overall, this indicates that the permitted discharges are less important for the overall environmental cost compared to the rest of the impacts in the value chain. The permitted discharges to sea from the drilling operation are highly regulated by authorities and under constant control in terms of monitoring and reporting.

Acknowledging that this survey does not include all environmental impacts (e.g. land use and biodiversity effects) and acknowledging that permitted discharges to sea are an area of high importance to the sector and society, it is notable that the cost of marine impacts is relative insignificant compared to the other impacts, e.g. the upstream impacts from mining of raw materials and production of steel and chemicals, emissions to air during the drilling operation a.o.

Many stakeholders - including operator, service providers, suppliers and regulators - have influence on the type of and usage of chemicals and consequently the emissions of chemicals to the environment, e.g. as permitted discharges to sea. On one hand the results of this analysis show that reduction in the use of chemicals and informed choices of chemicals with the lowest water footprint are viable ways forward in order to lower the total environmental cost. On the other hand the regulation does not necessarily provide a holistic view on these matters as the major task is to regulate the discharge and impacts in the actual operation.

The findings of this project demonstrate that NCA data can be used to prioritise emissions and mitigation in a broader perspective. The results also points at the fact that NCA data can be used to qualify the discussion with stakeholders on where companies and the sector can achieve the most benefit for the company, sector and the society in terms of invested money and focus. An interesting question to address could be whether it is sufficient to continue - but not increase - the high performance on permitted discharges and instead focus more on choice and usage of steel and chemical types and emissions to air during the well construction. The choice of materials and how this impact the environmental cost in the value chain is addressed in chapter 11.

10.4 Environmental cost divided on input materials and value chain tiers

In the figure below the total environmental cost in the value chain are divided between input materials. The figure clearly shows that chemicals and fuel are responsible for the majority of the environmental cost. The division of cost between materials is directly proportional with the amount of materials used, as illustrated in Figure 11-2.

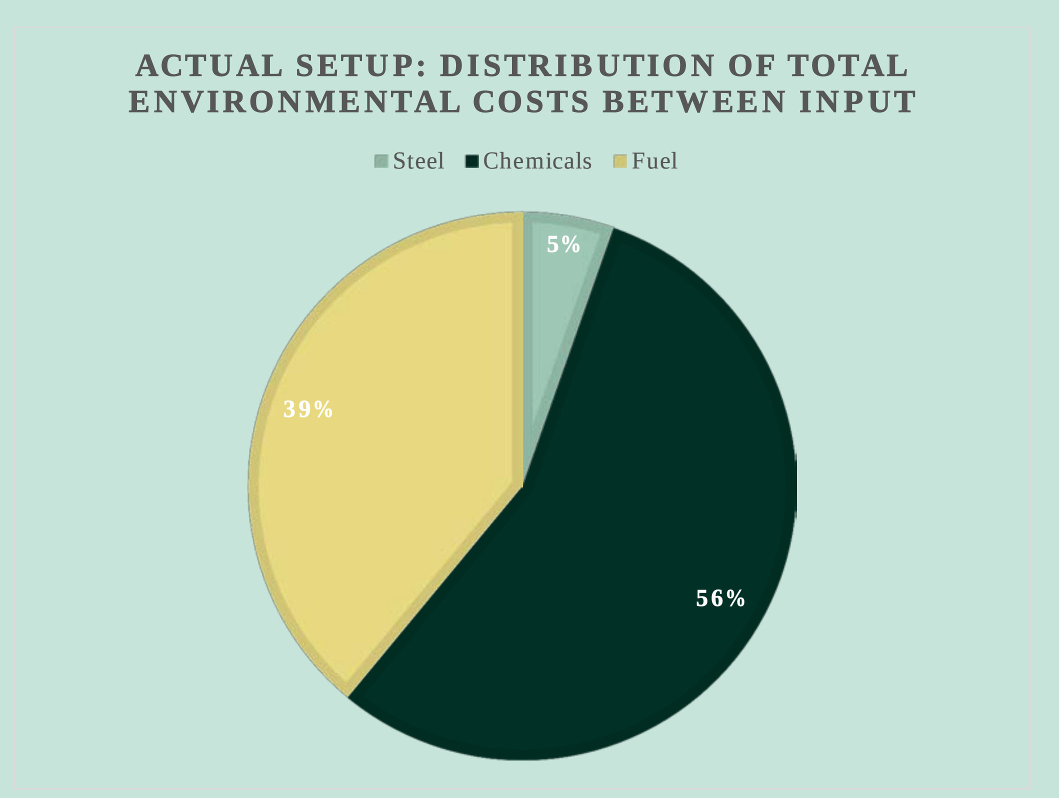

FIGURE 10-3: DISTRIBUTION OF ENVIRONMENTAL COSTS BETWEEN MATERIALS

In the figure below the total cost in the value chain has been divided between the tiers in the value chain.

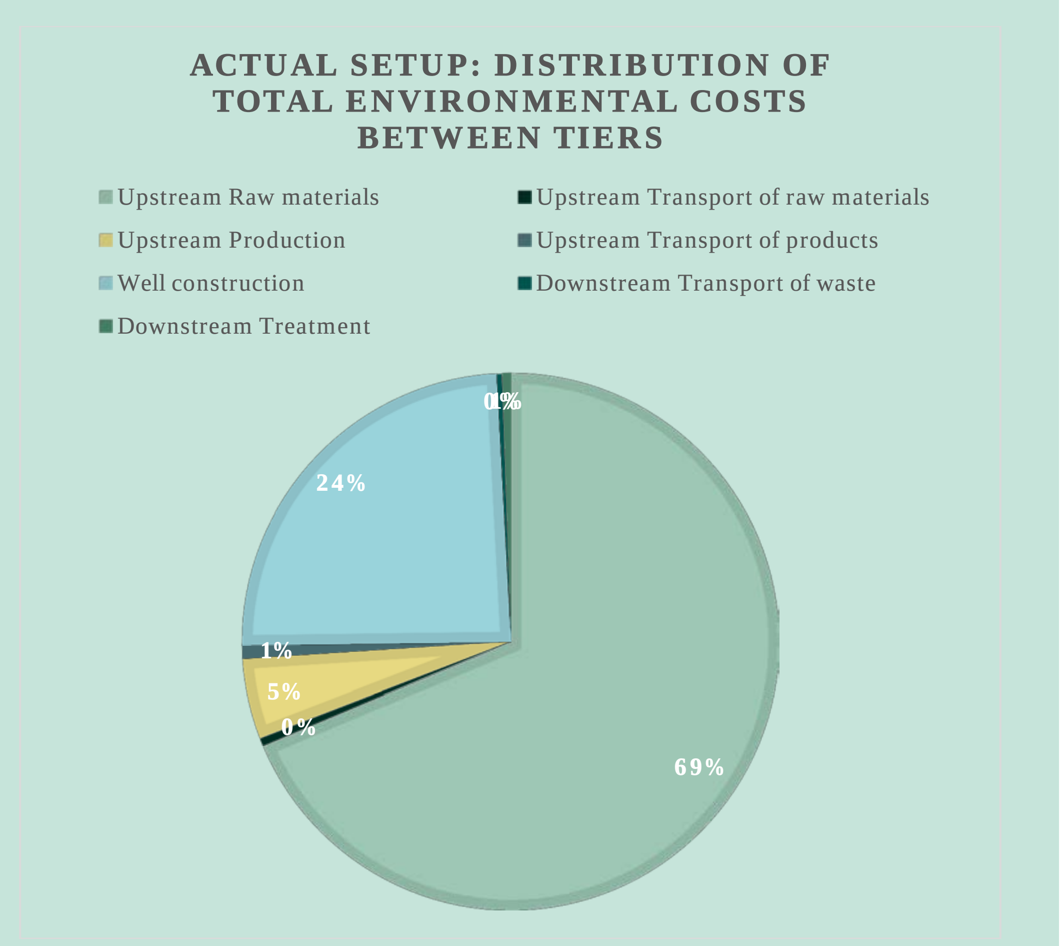

FIGURE 10-4: COMPARISON OF THE TOTAL ENVIRONMENTAL COST IN THE VALUE CHAIN DIVIDED ON VALUE CHAIN TIERS AND ACTIVITIES. PLEASE NOTE THAT TIER 'WELL CONSTRUCTION' INCLUDES EMISSIONS FROM OPERATION OF RIG AND OPERATION OF VESSELS AND HELICOPTERS FOR TRANSPORT OF MATERIALS AND PERSONNEL, WHEREAS EMISSIONS FROM PRODUCTION AND TRANSPORT OF FUELS FOR OPERATING THE VESSELS, RIG AND HELICOPTERS ARE INCLUDED IN TIER 'UPSTREAM'. SIMILAR APPROACH APPLIES FOR OTHER INPUT MATERIALS AND DOWNSTREAM ACTIVITIES.

The division of costs by value chain tiers clearly shows that the production of raw materials into fuels (raw oil production) and chemicals and steel (mining) accounts for the most substantial part of the environmental cost. It is also demonstrated that the cost of the impacts from actual well construction is approximately one quarter of the total cost, and approximately half the size of the cost of impacts in the upstream production of raw materials.

11. Using NCA data for optimising sourcing

This chapter analyses the environmental cost in the full value chain using type of material as a point of departure. The results demonstrate that NCA data are usable for deciding where to optimise sourcing in order to reduce the overall footprint.

In the figure below the cost has been divided by tiers in the value chain for each type of material. The illustration further indicates that the majority of the environmental costs relate to upstream production of raw materials for steel and chemicals. For fuel, the majority of costs are associated with the actual well construction secondly the upstream impacts.

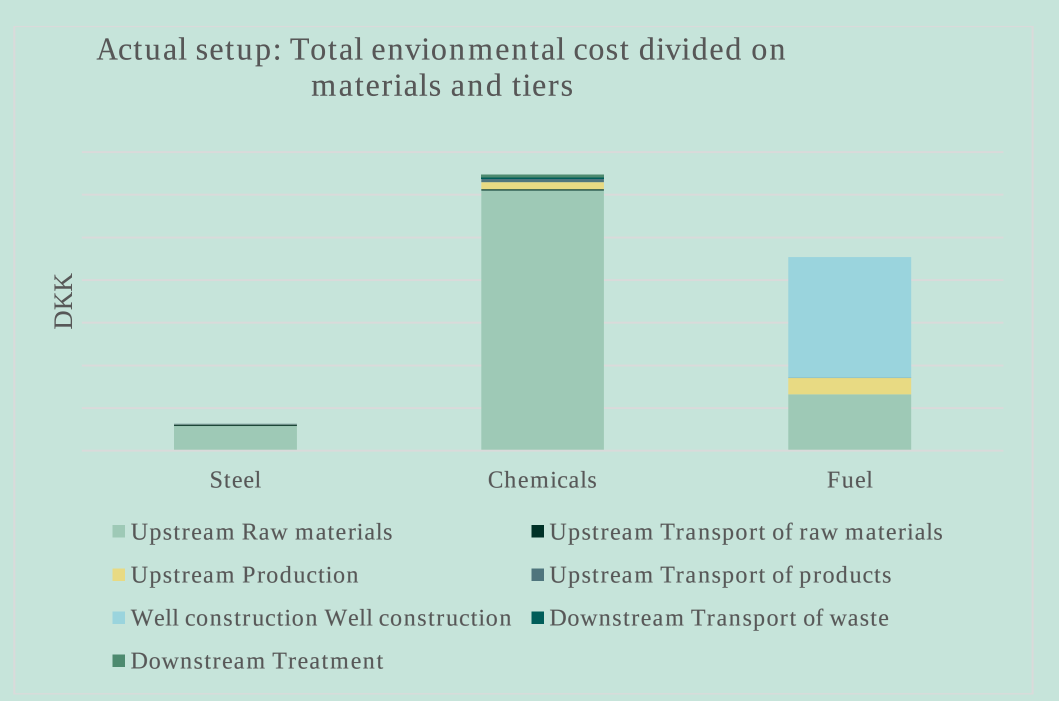

FIGURE 11-1: DIVISION OF TOTAL ENVIRONMENTAL COST IN THE VALUE CHAIN DIVIDED ON TYPES OF MATERIAL AND TIERS

In the figure below the environmental costs are divided by types of impacts pr. tonne input material used on the rig. The illustration shows that up- and downstream impacts on water bodies weighs heavily for chemicals and steel, whereas for fuels are impacts following emissions of NO_X that are responsible for the majority of cost pr. ton. The illustration also indicates that operational optimisation of the NO_X emissions on the rig may result in visible changes in the overall environmental costs.

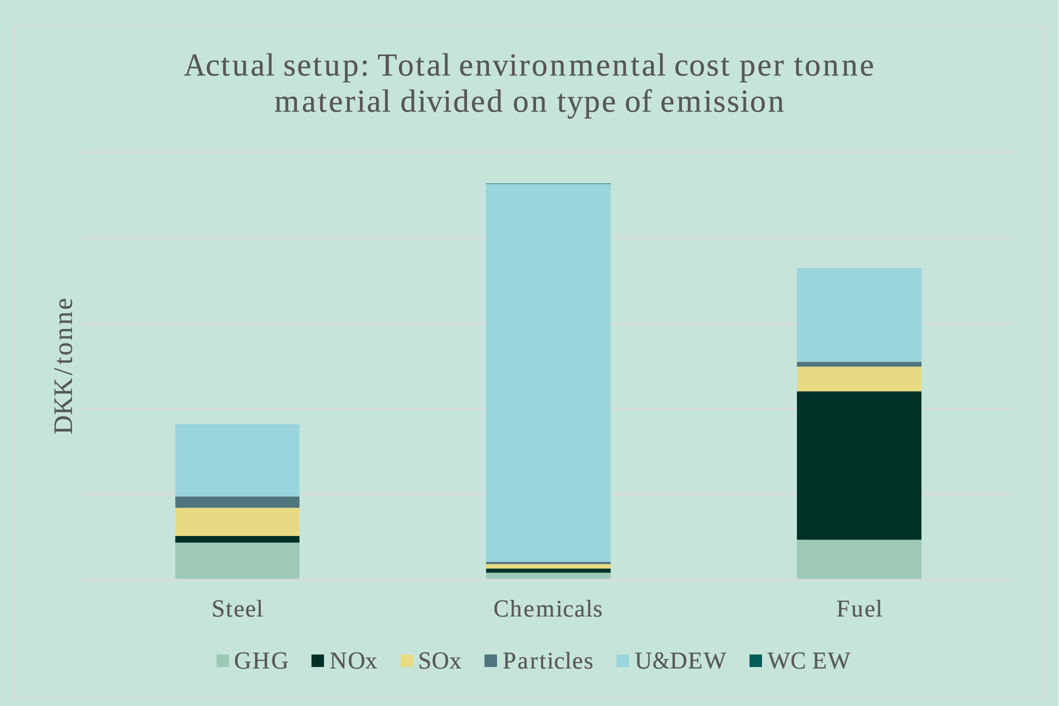

FIGURE 11-2: TOTAL ENVIRONMENTAL COSTS IN THE VALUE CHAIN DIVIDED BY MATERIALS AND TYPES OF EMISSIONS (PER TONNE INPUT MATERIAL)

Combining these findings with the finding in the previous illustration indicates that the largest impacts are related to water usage and discharge in the production of raw materials. This indicates that even small improvements in the upstream water consumption and discharge may have substantial effect on the overall environmental cost related to the well construction. It also indicates that sourcing chemicals with focus on water efficiency in the production phase may be a way forward for lowering the overall cost to the environment. A similar assessment for steel indicates that energy efficiency and water efficiency are relevant sourcing parameters.

As illustrated in chapter 7 there are some differences in the environmental emissions from upstream production and transport of the 3 steel types as well as for the 3 Group 1 chemicals addressed in the LCA. Differences are particularly clear on the upstream impacts from NO_X and usage and discharge of water.

These results, together with the previous observations indicate that improvements in the overall environmental cost of well construction can be achieved through an informed choice of materials. Such decisions may be based on LCA and NCA assessment or similar calculations of the environmental costs of each alternative material.

Historically environmental impact data on input materials are not requested nor readily available for the operator or the drilling service provider. On the other hand, data may be available on request on the understanding that such data may provide competitive advantages for the supplier of input materials. An example of a sector where such data is increasingly being used is the building sector: Here LCA assessments and Environmental Product Declarations are used to describe the impacts in the full value chain.

As many of the major emissions occur during the production of input materials there is a need to define requirements to the supplier about his suppliers of the raw material.

12. Using NCA data for optimising design and choice of technology

As mentioned in the scope this pilot project is aiming at demonstrating the usability of NCA data in operational and strategic decision making.

In this chapter the NCA results focus on the differences in cost pr. meter section and on cost of different choice of slop water handling to assess whether the NCA data is usable for decision making in terms of optimising design, e.g. in a new setup and choice of technology.

Calculated environmental cost pr. meter of the different sections includes all input materials and impacts in the full value chain. The environmental costs pr. meter are used to demonstrate what effects that may be achieved by optimizing the design of the well in terms of choice of length of each section.

Similarly the calculated environmental cost of different choices of slop water handling technology is used to demonstrate the usability of NCA data as basis for technological choices.

12.1 Using NCA data to optimise design and drilling operation

In the illustrations below the environmental cost pr. section, emissions type, and pr. meter drilled well are compared.

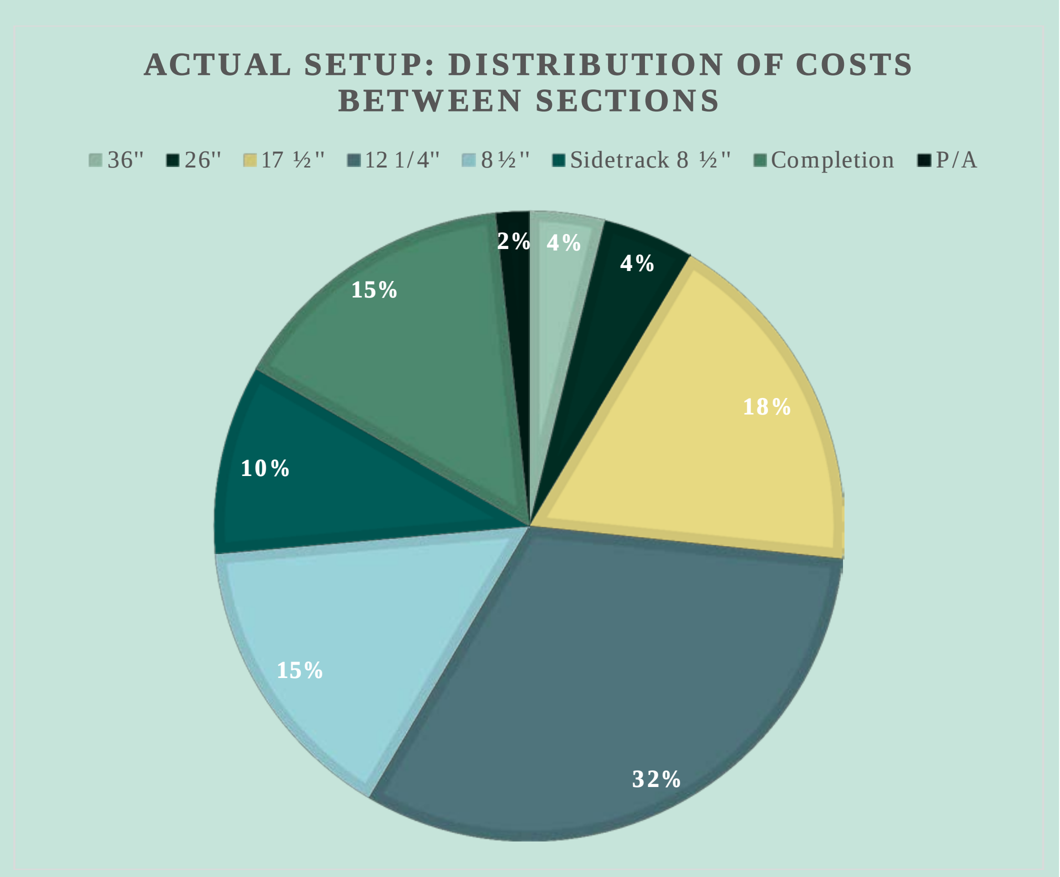

FIGURE 12-1: DISTRIBUTION OF THE TOTAL ENVIRONMENTAL COST IN THE VALUE CHAIN DIVIDED BETWEEN SECTIONS IN THE WELL.

The above illustration of the distribution between the sections show that in particular sections 17 1/2", 12 1/4", 8 ½" and completion accounts for substantial shares of the total cost.

The explanations should be found in the characteristics of the sections – like:

- length
- time
- up- and downtime
- volume of input material
- type of input material used

In Figure 12-2 the total environmental costs are divided pr. meter drilled well. It is seen that the cost level pr. meter varies substantially across the sections. The illustration shows that the major parameter in affecting the meter-cost is related to the usage of water and discharge to water bodies related to the input materials in the upstream parts of the value chain. In other words sourcing of input materials with as low water footprint as possible will lower the overall meter-cost.

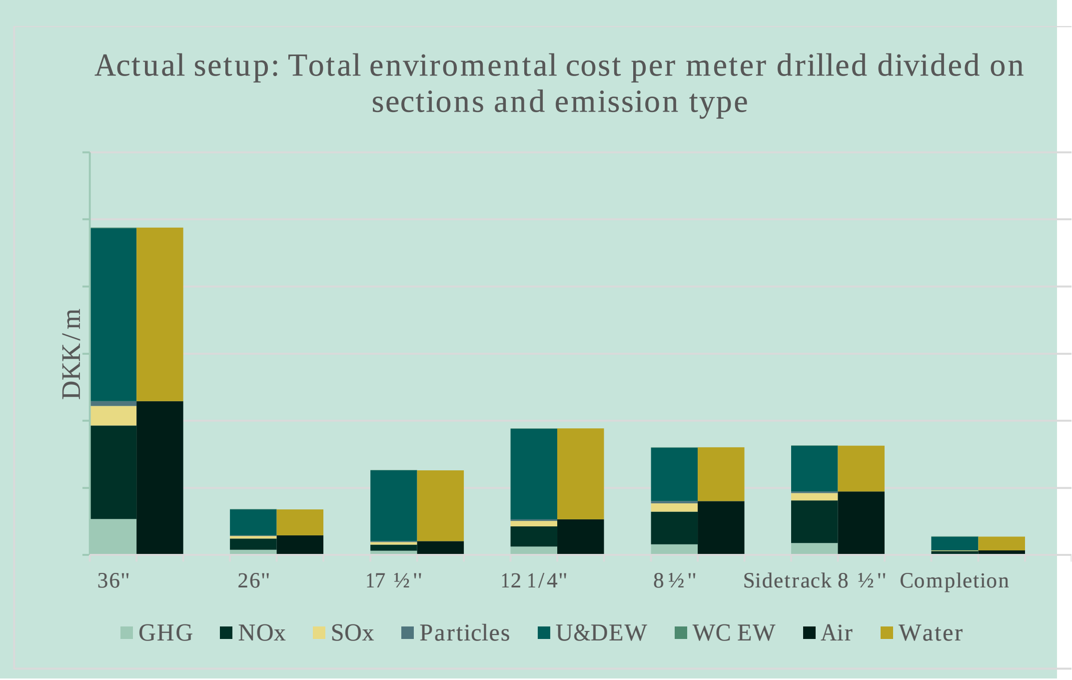

FIGURE 12-2: COMPARISON OF THE TOTAL ENVIRONMENTAL COST IN THE VALUE CHAIN EXCL. ENVIRONMENTAL COST RELATED TO COMPLETION IS EXCLUDED, AS NO METERS ARE DRILLED IN COMPLETION. COST PR. METER DRILLED WELL ARE DIVIDED ON THE TYPES OF EMISSION AND SECTIONS OF THE WELL

The figure also illustrate that the environmental costs pr. meter drilled well are highest for the section 36". The section 36" has the highest diameter (more steel pr. meter) but is one of the shortest sections. All impacts are therefore divided by only a relatively few meters. Here NO_X and impacts from water usage and water discharge accounts for the majority of impacts for all sections. The results open up for a discussion on how long the conductor section of 36" has to be. It is notable that costs associated with permitted discharges to sea (WC EW) are very low compared to other costs.

In the illustration below, the environmental cost pr. hour of drilling is presented. The cost is divided by the total rig hours that are the sum of up- and downtime. Please note that the chemicals used in the oil based mud in section 17½ and 12 1/4” are reused in the next sections.

The results show that the environmental cost pr. hour varies with approximately a factor approximately of 5 and that establishing of the section 17½" is significantly more expensive in terms of environmental cost than the other sections. Further examination of the data shows that this is partly due to extensive cost in the value chain related to water usage and discharge of water particularly from the production of chemicals, as is seen from comparison of the illustration and Figure 6-3, the length of the section and thus higher fuel consumption and the uptime for the section relatively to the other sections.

The illustrations demonstrate how NCA data, emissions and cost may be combined with both design of the well and operation of the drilling rig. Keeping in mind that efficiency in the offshore drilling is highly depending on, among other aspects, break down of equipment, weather situation, etc. and keeping in mind that financial cost efficiency is always given high priority. This pilot project shows that NCA data provides supplementary aspects to the discussion on costs and how to reduce cost to the benefit of both the company and society through design and optimisation of well construction.

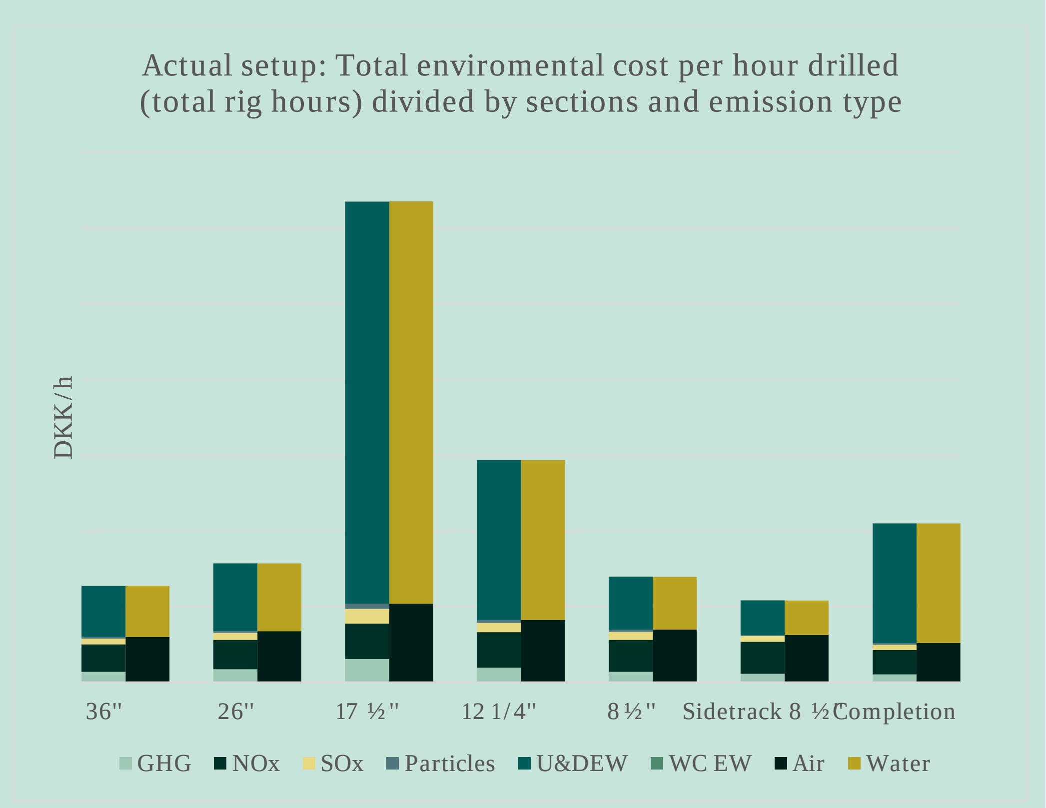

FIGURE 12-3: COMPARISON OF THE TOTAL ENVIRONMENTAL COST RELATED TO THE VALUE CHAIN PR. HOUR (TOTAL RIG HOURS)

The calculated environmental cost pr. meter drilled well presented in the Figure 12-2 and Figure 12-3 were used in the user interface tool to evaluate the changes in environmental costs following changes in the design of the well. Several alternative set-ups were tested assuming that section 36” needed at least 40 m’s to ensure sufficient space for equipment and that the total length of the well was constant and that the depths intervals were the specific steel types were used were respected. The testing showed that the total environmental cost in a value chain perspective was not significantly impacted by changes in the length of the sections as described, and that the majority of the changes were seen in the division of environmental costs between types of emissions.

The marginal changes in the total environmental costs are determined to be due to the fact that the majority of the environmental costs are associated with upstream activities (also see Figure 10-1). In other words, changes in design of the well, as described, do not have a substantial effect on the total environmental costs but more in the division of the environmental cost between types of emissions. Reduction of the footprint should instead be sought in the sourcing of the input materials based on their environmental cost levels.

12.2 Using NCA data to optimise choice of technology on slop water treatment

As mentioned in the scope the project aim at testing the usability of NCA data in providing informed decision basis in choice of technologies. In this project the handling of slop water was in focus as a new technology. The RENA slop water treatment unit was installed on the drilling rig during well construction.

In chapter 7 the emissions from three slop water treatment scenarios was addressed. The scenarios were:

- **Actual set up** where the Rena unit was installed during the activity and was therefore only partly used. Thus part of the slop water was sent to shore and part of the slop water was treated in the RENA unit
- **Scenario 1: Conventional slop water treatment** onshore. All slop water from OBM drilling is transported to Soil Recovery A/S in Nyborg for treatment.
- **Scenario 2: RENA slop water treatment unit** of all slop water from OBM drilling. Processed water is discharged to sea in compliance with permits. Retentate – the remaining waste stream from the RENA unit - is treated on-shore at Soil Recovery A/S in Nyborg

From the figures below the environmental costs through the full value chain related to the slop water treatment scenarios are presented.

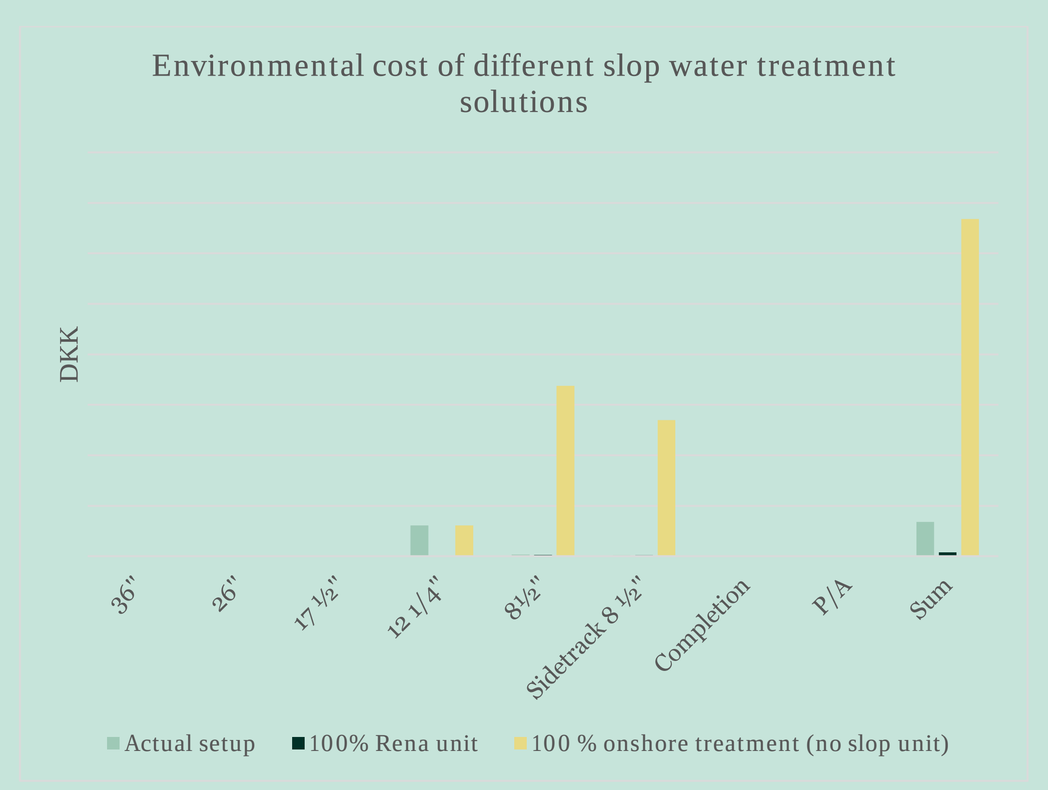

FIGURE 12-4: COMPARISON OF THE ENVIRONMENTAL COST ASSOCIATED WITH THE SLOP WATER TREATMENT SCENARIOS.

Please note that environmental cost associated with the production, installation and the transport of the RENA unit are not included.

The figure illustrates that operation of a RENA slop water treatment unit reduces the overall environmental cost to society for handling OBM slop water substantially. This is both compared to a scenario where all the OBM slop water is transported to and treated at Soil Recovery or a scenario where part of the OBM slop water is treated at Soil Recovery (actual set up of drilling operation).

The majority of the impacts are related to fuel consumption for transportation of the slop water. The calculations are based on the assumption that the fuel consumption both to and from the rig is included (conservative approach).

These data strengthen the decision basis used for selecting the slop water treatment approach, e.g. deciding whether to that RENA slop water treatment units or similar units should be installed.

Even though installation of the RENA SLOP unit on the rig results in a significant reduction of the environmental cost associated with transport and handling of slop water, the downstream transport and handling of waste only accounts for a very small fraction of the total environmental cost associated with the value chain of the drilling operation

The example clearly demonstrates how NCA calculations may be used to support choice of technology and qualify discussions between both customer, supplier and regulator. Both from an operational point of view as well as from an environmental point of view the RENA unit is a good investment.

13. Sensitivity testing of results

As mentioned in chapter 8 the valuation estimates used are critical for the relative division of environmental costs both in the value chain and on emission types. In this chapter the overall results are sensitivity tested in order to assess if the conclusion in the previous chapters are robust.

The sensitivity testing covers both the assumption on water usage and discharges to water, especially in up- and downstream tiers and the variation in valuation estimates.

13.1 Water usage and discharges

The valuation of the discharges to water and the impact on water bodies are based on public and stated prices. Some of the prices are based on valuation studies through which the value is estimated, others by using the price paid for water treatment together with the green taxes. In both cases the prices are to express the value to society for the impact on water even when the service is not a traded product in the market. For example, some of the values refers to the limitations in further water consumption due to contamination or water scarcity others to the direct impact on the possibility of using the water.

The estimate of environmental cost related to upstream and downstream emissions to water bodies use an estimated amount of water discharged from the activity. The estimated amount of discharged water is in the actual setup set to 50% of the water usage for steel and chemical production and to 100% for fuel production, based on data from environmental reports from the actual Danish oil activities.

From the illustration in the previous chapters it is seen that costs related to up- and downstream emissions to water bodies (U&DEW) are significant. It is therefore relevant to reassess if the assumptions used are acceptable. As mentioned, the environmental cost associated with U&DEW for fuel production is fairly accurate as it is based on reporting from the actual Danish activities involved and well as Danish valuation estimates. The estimates on steel production and chemical production are uncertain and may be either bigger or smaller depending on how well the companies in the value chain manage their water and in which way the impacts on the water bodies are assessed.

In order to assess the sensitivity of the conclusions the following cases where examined:

1. Actual setup: the estimated amount of discharged water is set to 50% of the water usage for steel and chemical production and to 100% for fuel production, based on data from environmental reports from the actual Danish oil activities.
2. No recycled water for any input materials: it is assumed that all used water upstream in chemical and steel production is discharged to the sewer system and needs treatment (0 % recycling/reuse elsewhere). Water discharge from fuel production is set to 100% of the water usage.
3. 90% recycling of water: it is assumed that the water efficiency is higher for both chemical and steel production and that discharged water equals 10 % of the used water (90% is recycled/reused elsewhere). Water discharge from fuel production is set to 100% of the water usage.

The results are presented below in comparison with the value chain environmental cost division for the actual well construction. The illustrations show that even in the case where the discharged water is equal to the usage (0% recycling/reuse elsewhere) the environmental costs related to discharge to water bodies compared to other parameters are still substantial. The share of the total environmental cost varies between approximately 40 % (90% recycling/reuse) over approximately 70 % (actual operation) to approximately 80% (no recycling). For the case with 0% recycling/reuse of the water elsewhere, the total environmental cost is increased with approximately 50%. For the case with 90% recycling/reuse the total environmental cost is reduced with approximately 40%.

The sensitivity testing on the inventory for water usage and discharge shows that no matter the assumptions the cost related to impacts on water bodies are still responsible for the majority of the total environmental cost in the value chain. It also shows that recycling of water in all parts of the value chain is an important task in lowering the overall environmental cost related to establishing an offshore well.

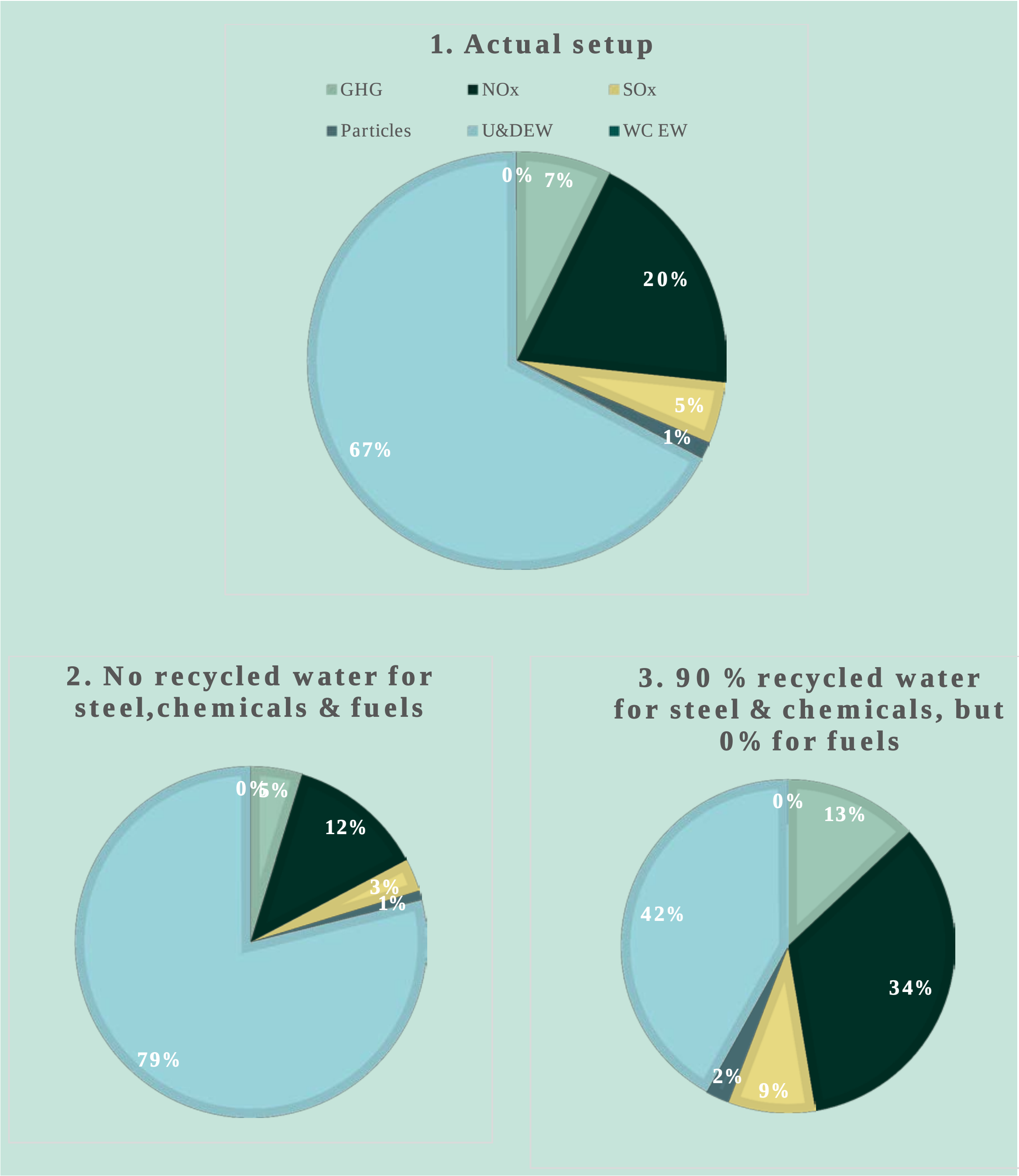

FIGURE 13-1 SENSITIVITY ANALYSIS - VARIOUS DEGREE OF RECYCLING OF WATER: 1) ACTUAL SET UP OF WELL CONSTRUCTION ASSUMING 50% RECYCLING FOR STEEL AND CHEMICAL PRODUCTION AND 0% RECYCLING FOR FUEL PRODUCTION 2) NO (0%) RECYCLING OF WATER IN ALL UPSTREAM TIERS FOR STEEL, CHEMICALS AND FUELS AND 3) 90% RECYCLING OF WATER IN ALL UPSTREAM TIERS FOR STEEL AND CHEMICALS, BUT ZERO RECYCLING FOR FUEL PRODUCTION

13.2 Valuation estimates

As mentioned three supplementary set of valuation estimates have been used to test the robustness of the results based on the key estimates. The first sensitivity scenario is with low estimates, the second with high estimates and the last one with Trucost and other's estimates derived from the Novo Nordisk EP&L. In the graph beneath the total environmental cost calculated for the different scenarios are illustrated per m drilling.

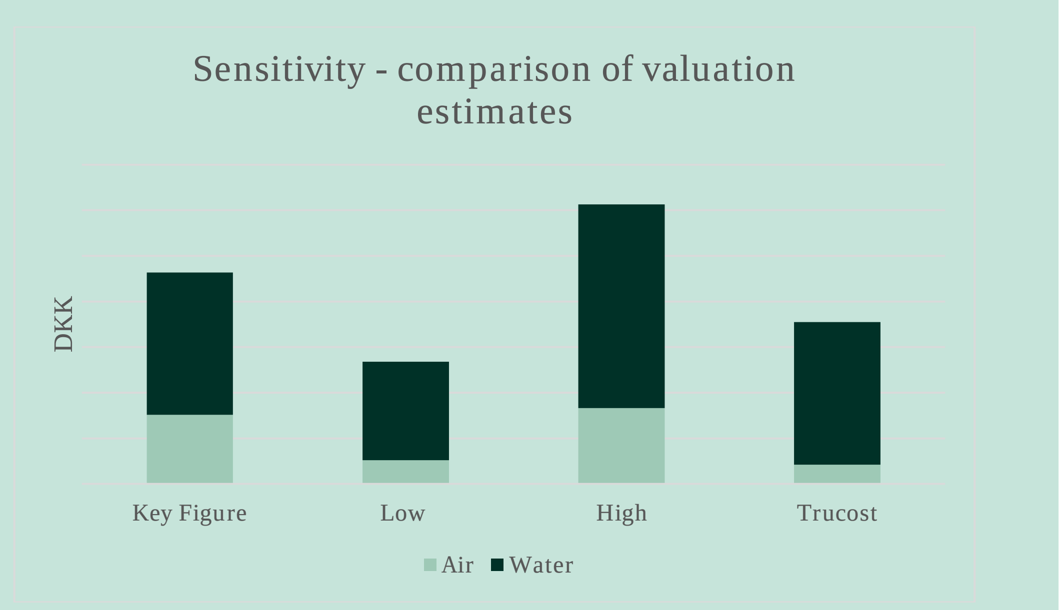

FIGURE 13-2: COMPARISON OF TOTAL ENVIRONMENTAL COST PER METER WELL BY USING DIFFERENT VALUATION ESTIMATES. SEE TEXT FOR EXPLANATION

The illustration shows that the used valuation estimates (key figures) represent an environmental cost estimate comparable with the other estimates in terms of order of magnitude: One is larger (high scenario) and two are smaller (low scenario and Trucost a.o.'s estimates).

If a low set of valuation estimates is chosen the total environmental cost will be approximately1/3 lower and if the high estimates are chosen the result will be approximately 1/3 higher. If the prices from Trucost a.o. are chosen the results will be approximately ¼ lower.

The illustration shows that the division between air impacts and water impacts differs in the different valuation scenarios: The division of air and water impacts is similar in the scenarios using key figures, low estimates and high estimates, whereas the share of the water impacts is relatively higher using the Trucost a.o. estimates.

This is detailed even more in the following illustration: The impacts from the different sensitivity scenarios are illustrated as the distribution of environmental impacts. It is seen that there are few differences between the key figure estimate and scenarios low and high, whereas the scenario using Trucost a.o. estimates differs from the others. This is primarily due to the low air valuation estimates used by Trucost a.o. On the other hand, Trucost uses a high valuation for CO_2 but due to the relative low CO_2 emissions the effect on the total environmental cost is minor.

For all three scenarios up and downstream impacts on water keeps representing a major share of the total cost.

It is concluded from the sensitivity testing that the usage of the key valuation estimates used for the NCA results are a robust choice of valuation estimates.

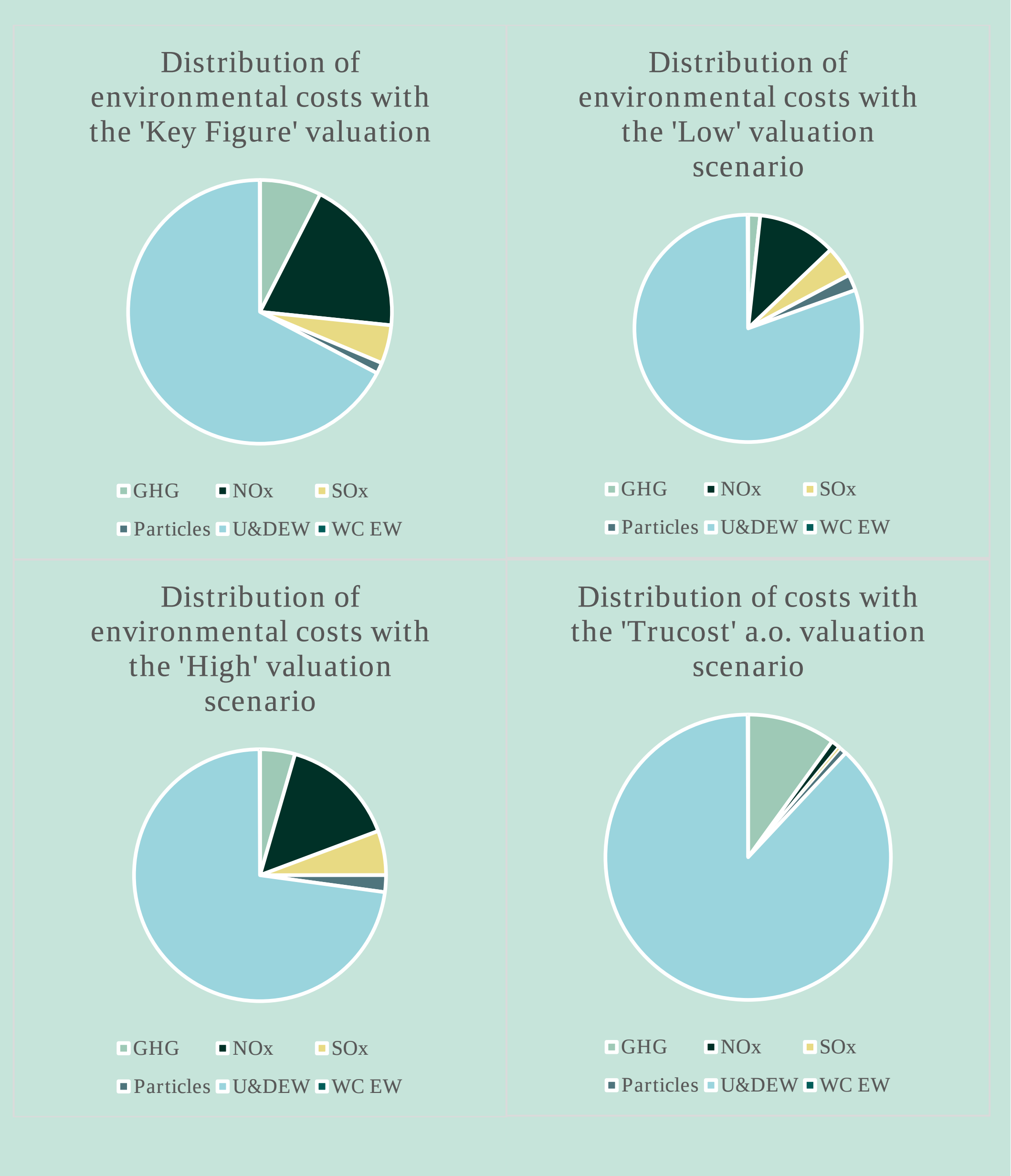

FIGURE 13-3: DISTRIBUTION OF THE TOTAL ENVIRONMENTAL COST ON EMISSION TYPES USING KEY FIGURES, LOW ESTIMATES, HIGH ESTIMATES AND ESTIMATES FROM TRUCOST A.O.

14. Thought Experiments on unintended discharge and flaring

Environmental cost associated with unintended discharge during well construction and flaring during testing of the well are addressed as thought experiments, which are hypothetical scenarios, as no flaring nor unintended discharges have occurred during the construction of the HA-1 well.

The thought experiments are used to assess and if possible demonstrate the usability of NCA data on unintended discharges and flaring in order to compare the environmental cost of the unintended discharges and flaring with other environmental cost.

14.1 Using NCA data on unintended discharges

Unintended discharges are included as thought experiments addressing the societal cost related to unintended discharges of red and yellow chemicals or oils in volumes of up to 100 kg pr. unintended discharges.

As a thought experiment it is assumed that an unintended discharge of oil of a volume of 100 kg of diesel oil (approximately 0.08 m^3) occur during the well construction. As worst case scenario, the unintended discharge is assumed to result in an affected area of approximately 0.4-1.2 km^2, thus ignoring the effect of evaporation, emulsification, biological degradation during the spreading process. For comparison, a similar size of unintended discharge of red chemicals will only affect a few percent of the area affected by unintended oil discharges as a 100 kg unintended discharges of red chemical (approximately 0.03-0.1 m^3 depending on density) according to calculations 'only' affect an area of approximately 20,000 m^2. The affected area estimate for unintended discharge of diesel is so much higher than for chemicals due to the fact that chemicals will be mixed in 30 meters of water whereas diesel is a non-miscible fluid that will form a film on the surface.

Due to turbulence from breaking waves and wind action some diesel can be assumed to affect the upper 1 m of the water column. Due to the relatively small size of the unintended discharge no remediation is assumed. Remediation could be adding dispersion agents making the plume more bio available, but potentially also affecting a larger part of the water column.

If evaporation is included in the estimates, it is reasonable to assume that the affected area is smaller than estimated: Surveys shows that a substantial part of unintended diesel discharges is evaporated during the first three to four hours after an unintended discharge. This is illustrated in the figure below, where Group 1 is diesel, Group 2 and 3 light and heavy crude oil and Group 4 represents bunker oil. The evaporation results presented indicate that the environmental impact will be significant less than the estimated affected area of sea surface of approximately 1 million m^2 for an unintended discharge of 100 kg diesel.

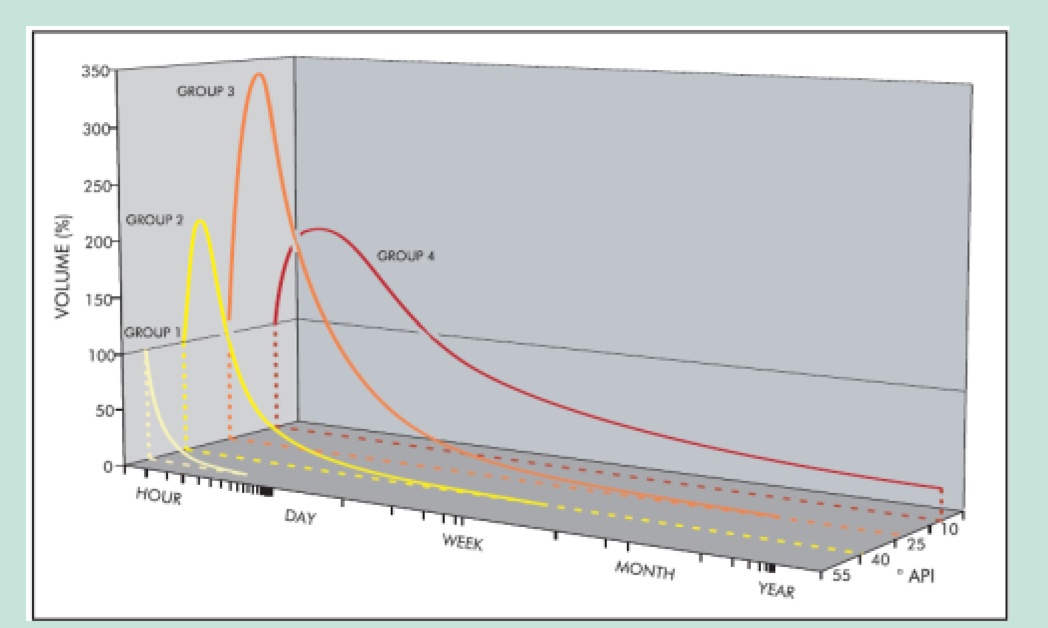

FIGURE 14-1: VOLUME OF OIL AND WATER IN OIL EMULSION ON THE SEA SURFACE. THE CURVES REPRESENT AVERAGE WEATHERING OF DIFFERENT OIL TYPES (ITOPF, 2006). GROUP 4 REPRESENTS BUNKER OIL, GROUP 2 AND 3 LIGHT AND HEAVY CRUDE OIL, RESP. GROUP 1 REPRESENTS DIESEL. REFERENCE: ITOPF 2006: ITOPF TECHNICAL INFORMATION PAPERS: "FATE OF MARINE OIL SPILLS", http://www.itopf.com/tip2.pdf

The actual impact of oil pollution on a marine protected area with a significant value to society also depends on a variety of physical and biological parameters. It is therefore not possible to say exactly how large the impact will be when it reaches the sensitive area (e.g. Dogger Bank). There is an enormous variation in response and effect on different species: Effects in the top of the water column are expected to have an impact on birds, but the severity of the impact depends among other things on the avoidance behavior, which again depends on seasonal differences. Effect on the lower part of the water column may directly affect fish and fish eggs and larvae, which again may affect the higher trophic levels in terms of e.g. prey availability.

Taking into account the relatively small size of the unintended discharge and the average water depth at the Dogger Bank of 25 m, the affected upper 1 m represent approximately 4 % of the water volume. This may be used as a spatial impact reduction factor for the impact of an unintended discharge on Dogger Bank or a similar sensitive area.

Using the key valuation estimate of 7.5 million DKK/km^2*year based on the survey on willingness to pay to protect Dogger Bank (chapter 8), together with the spatial reduction factor the approximated environmental cost associated with an unintended discharge of oil of 100 kg will be approximately DKK 300,000, not taking the temporal considerations into account:

As mentioned the effect on biota is depending on various aspects: For the purpose of the thought experiment it is assumed that the effect of diesel on the biota in the affect layer of the water column is vanishing by approximately 1 day, 1 week or 1 year, the latter being relatively conservative not taking normal avoidance behavior and the size of the unintended discharge fully into account. Thus a temporal reduction factor of 1/365 = 0,3%, 1/52 = 2% or 1/1=100% may be applied for the Thought Experiment.

Combining the spatial impact limitation to the surface layer and the temporal limitations results in environmental cost associated with an unintended oil discharge of 100 kg diesel oil (0.08 m^3) to between less than DKK 1,000 approximately DKK 7,000 and approximately DKK 300,000, the latter being a relative conservative estimate. Please note that these calculations should be taken as indications of magnitudes with due respect to the assumptions used.

In chapter 8.1.5, two surveys are proposed used for sensitivity testing of the unintended discharge[1] results. The surveys estimate the willingness to pay to avoid marine oil spills. Basically all three valuation estimates indicate a very high willingness in the society to pay to avoid marine oil spills. The difference between the three estimated costs indicate that environmental valuation estimates for unintended discharges are associated with some uncertainty and conclusions should be indicative.

The Thought experiment confirms that unintended discharges may be associated with quantifiable environmental cost. It is important to state that unintended discharges should be avoided at all time and that major unintended spills from platforms, like blow-outs, may have substantially larger impact than these relatively small spills illustrated in the Though Experiment. This is due to different oil types, spill locations and last not least spill volumes, which imply qualitatively different processes for mixing and impact. However, the Thought Experiment like this, which is based on transparent, systematic and scientific methods, may open up for new aspects in the discussion on how the marine sector may reduce the overall footprint of their activities and how benefits for society are reached the easiest way with the resources available. Such dialogue could be combined with the work in the ongoing BE-AWARE project within the Bonn Agreement framework (http://www.bonnagreement.org/be-aware) which comprises environmental and socio-economic vulnerability assessments and risk due to unintended oil discharges in the North Sea with the co-operation of all North Sea countries.

The thought experiment demonstrates that a combined assessment of the socio-economic, physical and biological features is the way forward in assessing the risk and relevant mitigation in case of all kinds of unintended discharges at sea, whatever geographical location. To expand the approach to deal with larger spill sizes, it requires a more detailed handling of the variability of exposure and effects. This is feasible by taking into account seasonality, hydrological and meteorological conditions, which play a role in determining the fate of oil and therefore also exposure time for various species. Knowledge on specific species in the spill zone and potential variations in their sensitivity to oil exposure should also be taken into account.

14.2 Using NCA data on flaring during testing of well

Environmental cost associated with flaring during testing of the well is included in the calculations as a Thought Experiment. Assuming a flaring of 1 Sm3 gas and using the valuation estimates presented for air emissions in chapter 8.

As a Thought Experiment it is assumed that a similar amount of gas as was flared on the neighboring wells is flaring during a fictitious testing of the HA-1 well. The environmental cost of flaring is calculated and presented in the figure beneath. The illustration shows that especially SO_X emissions are responsible for environmental cost associated with flaring. GHG and NO_X accounts for comparable environmental costs.

Calculations shows that the environmental cost associated with a potential flaring during testing accounts for less than 1% of the overall environmental cost in the value chain. For comparison the environmental cost associated with permitted discharges during the well construction accounts for significant less than the environmental cost associated with the fictitious flaring during well testing.

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[1] Willingness to pay among households to prevent coastal resources
from polluting by oil spills: A pilot survey, 2009, Xin Liu, Kai W. Wirtz, Andreas Kannen, Dietmar Kraft
An Accidental Oil Spill Along the Belgian Coast: Results from a CV Study, Karl van Biervliet, Dirk Le Roy and Paulo A.L.D. Nunes, 2006

Flaring costs are included in the user interface and can be used in assessing optimization focus in the operation.

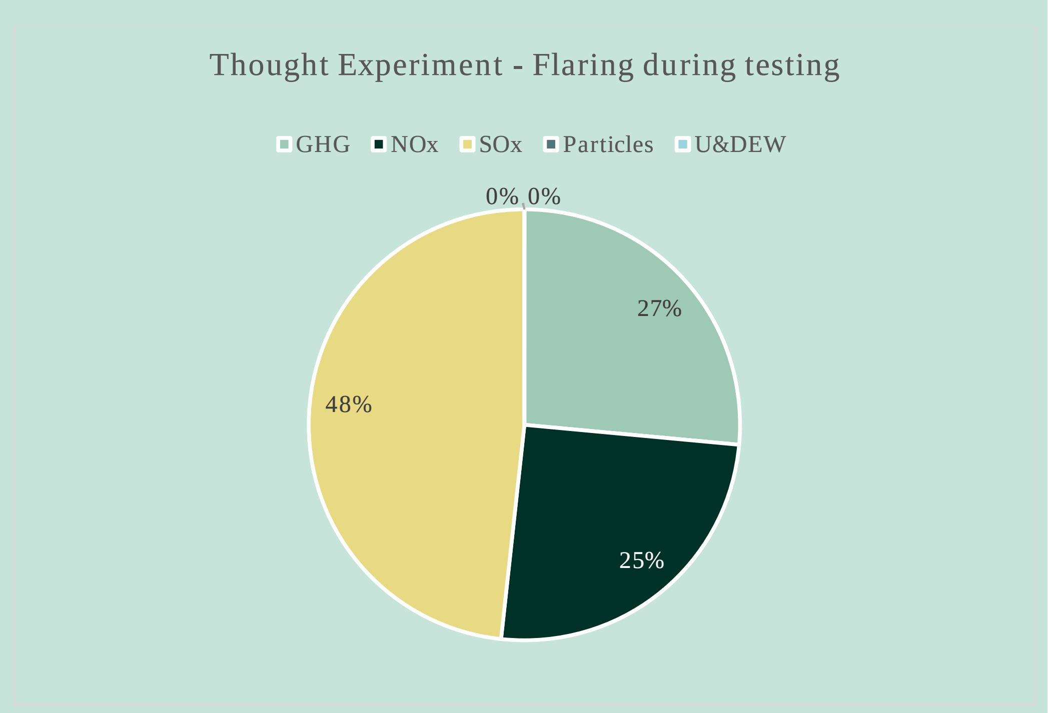


FIGURE 14-2: ENVIRONMENTAL COST OF ASSUMED FLARING DIVIDED ON THE EMISSIONS

15. Strategic use of NCA data

As mentioned in the first part of the report, the objective is not to provide a full account for MD and DONG but to demonstrate how NCA data for a specific scope may be used to support decision making in the business.

As mentioned in the previous chapters NCA data as presented in this report may in various ways be used to qualify the decision basis. In the following some more examples are presented:

15.1 Reporting and environmental management

The cost to the environment – whether partial or total - may be used for reporting to stakeholders. It is increasingly necessary for companies to proactive address the changing expectation of key stakeholders – including consumers, communities, regulators, shareholders, NGOs and media – on how businesses measure, value, manage and report their effects on environment and society.

As an example, in Demark annual reporting is increasingly focusing on the societal responsibility and NCA data may be used to demonstrate how the company prioritizes their initiatives and how they put this societal responsibility into play.

As demonstrated in the data in previous chapters the environmental cost to the society may be reduced faster if the company to a higher degree use their managerial focus and invested resources in other parts of the value chain without lowering the quality of the environmental work performed within the gates of the company. The relatively low environmental cost of e.g. permitted discharges to the sea compared to the higher costs related to NO_X during the well construction or to the water usage and discharge in the chemical production are examples on how NCA data may qualify companies' decision to re-focus their environmental effort and improvements without compromising existing permits. NCA data may be used to prioritize the impacts and initiatives as well as it may be used to measure and document the progress.

Most ISO systems and management systems require documented continuous improvements and the examples shown in this project show that NCA data may be used to demonstrate such continuous improvements – not only as improvements inside the 'gate' but also on a societal scale.

15.2 Design of more sustainable solutions

In this demonstration project the assessment of the RENA slop unit is a good example on how NCA data may be relevant for decision on investment and reporting purposes in commercial situations: The NCA data allowed for a comparison between the conventional slop water handling and the new RENA slop water unit, and clearly showed the benefits following installation of the RENA unit.

Such NCA information allows for comparison of different products and services provided by suppliers before investments. From a service provider or supplier point of view the NCA data may be used to improve competitiveness of their services and products.

The tool developed for DONG and Maersk Drilling is also an example on how NCA data may be used for design of solutions. The tool allows for a choice of lengths of sections, size and type of unintended discharges and amount of flaring and calculates the total environmental cost related to these choices using the unit prices derived from the actual drilling operation. Of cause the tool has some limitations as it is based on an actual drilling operation using very specific techniques, input materials and processes (e.g. HTHP processes and Mudcube unit) unique for the rig as well as it is penetrating unique sediments and is based on valuation estimates unique for the actual setting. Nevertheless the tool may be used to test and compare different setups of wells as long as the conditions are similar to the actual well. It may also be used for internal learning purposes, e.g. through investigating if alternative set up's of the well could have reduced the overall environmental cost. As the testing of the tool and the results in general indicated that substantial parts of the environmental costs are associated with the upstream activities, it is suggested to develop a tool that allows for comparison of upstream environmental cost of specific chemicals and steel types for sourcing support.

Thus the NCA tool – or similar tools - may be used to forecast the environmental cost following certain choices – and again provide supplementary information for the decision making when planning a well construction. Substantial data reusable in other tools is available in the tool developed in the project. When designed for the purpose similar tools may also be used for assessing the benefits following new business models, such as take back solutions e.g. on packaging of chemicals a.o.

15.3 Assessing unintended discharge through NCA data

The project demonstrated that a combined assessment of the socio-economic, physical and biological features is a way forward in assessing the risk, impacts and relevant mitigation in case of different kinds of unintended discharges at sea, whatever geographical location. The results are independent of whether the unintended discharge is related to drilling, vessel transport or other activities at sea. In many situations unintended discharges are addressed with same effort and emergency plans no matter type and size of unintended discharges. The Thought Experiments performed in this project indicates that stronger knowledge on the environmental cost of unintended discharges may be used to design monitoring and emergency responses with a more cost-effective use of resources.

15.4 Dialogue with regulators

The NCA data may furthermore be used for qualifying the dialogues with regulators. The NCA data may show that certain part of the value chain or certain emissions are of significant lesser or bigger importance than others. Most regulation is focused inside the business premises - in this case on the rig - and on achieving a high reliability in performance. The NCA data may be used for prioritizing both impacts and regulation in order to achieve most benefits from the resources available – not only in the actual operation but in the full value chain.

15.5 Asset management

The NCA approach may also come into play in terms of managing the company's social license to operate.

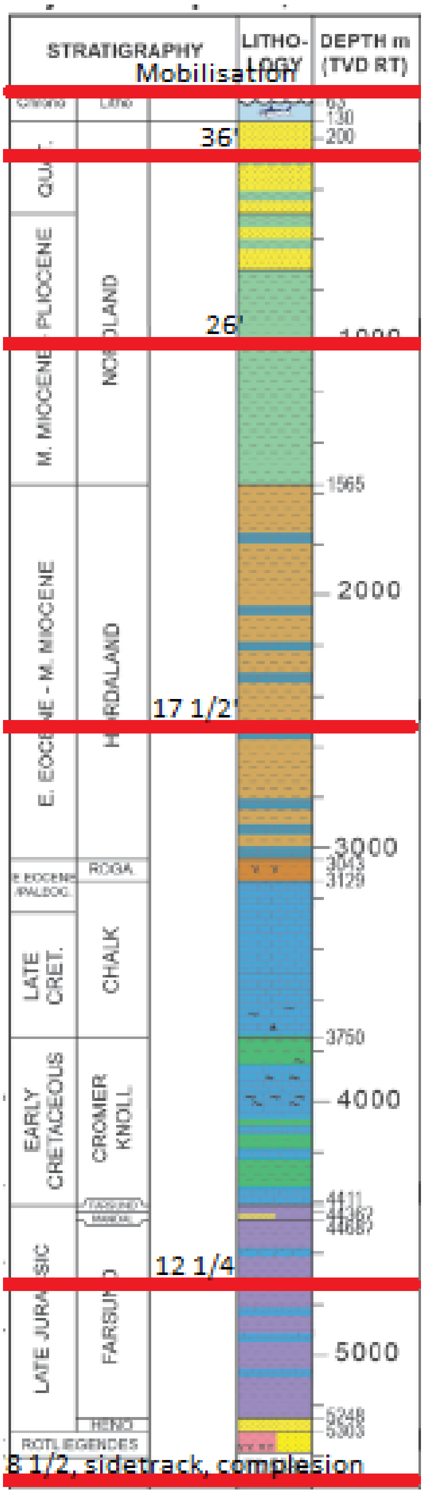
Local and national communities provide infrastructure, social support and an educated work force to the companies, while the global community grants the permission to use environmental amenities. Most of these scarce resources are provided to the company free of cost and, as a result, are not recorded anywhere in the financial accounts of the company. The value of these environmental amenities may be defined as the company's social license to operate and is thus an asset provided by the society.

With increasing regulation and increasing demands from customers and NGOs, this is increasingly becoming an asset given by society with the expectation that the company takes good care of the asset. A NCA similar to this NCA may be used as a baseline for the value of the asset. Periodic NCA accounts may show how well the company takes care of the asset, how it is improved or depreciated due to operational and strategic decisions. Putting this NCA into play in terms of asset management the companies could decide to improve e.g. the water footprint of the well by choosing chemicals and steel with the lowest water usage and account the improvements in the value of the asset.

16. References

All references used are included in the text or appendices either directly, as footnotes or as reference list in the appendix.

Appendix 1 Strata and sections



Appendix 2 Supplementary inventory data

This appendix presents supplementary inventory data.

Fuel and Electricity – downstream at Soil Recovery A/S

The table below presents the emissions for the actual transport of waste to Soil Recovery, that is, 7,070 tonnes cuttings, 219 tonnes slop water and 13.5 tonnes Retentate.

Soil Recovery A/S' Environmental Report from 2014 presents the overall environmental impacts following operation of the treatment plan (named K57) that handles waste from offshore. The plant treated a total of 3,970 tonnes of waste during 2014, which is assumed to be a combination of slop water and cuttings with mud residuals. As the drilling of HA-1 delivered a total of 7,302.5 tonnes of waste to Soil Recovery during the drilling period in 2014-2015, it is assumed that these data are representative for the inputs used and emissions from treatment of the actual drill cuttings.

According to the environmental report inputs to the plant were 3,970 tonnes of waste, 651 MWh, 401 m^3 water, and 4 m^3 of diesel. According to the report, the treatment of the waste in the treatment plant resulted in emissions to air of 414 tonnes of CO_2, 282 kg of NO_x, and 29 kg of SO_2.

The treatment includes a heating process transferring the chemicals and oil residues to either a water phase or an oil phase. According to the report, the water phase amounts to 1,660 m^3 of process sewage water and this is together with 97 m^3 of sanitary sewage water (excl. rainwater of 1,540 m^3) led to the local sewage water treatment plant after a flocculation and filtration. The local sewage treatment plant is under environmental approval and control according to Danish Law. The content of chemicals in the water phase is unknown and may not easily be estimated from the monitory data from DONG and Maersk Drilling. For the purpose of this assessment the impacts of handling the water phase is calculated using the following assumptions: Only impact on water bodies in terms of waste water discharged to local sewage water treatment plant is included and all other impacts are set to zero. The remaining solid phase (cuttings, dust a.o) amount to a total of 2,307 tonnes which is sent to a landfill next to the treatment plant. The landfill is regulated according to Danish law. The impacts on land and water from landfilling are set to zero.

Due to a very short distance, emissions from truck transportation from the treatment plant to the neighboring landfill is considered negligible and is set to zero. According to the report, materials to reuse and incineration are 4.7 and 2.7 tonnes respectively and final products including packaging is reported as 189 tonnes. The environmental impacts from these materials to transport/reuse/resell are excluded of the calculations as the type, use and value chain of the products that they displaces are unknown.

These data are adjusted to inputs and emissions, see table below.

TABLE: ENERGY INPUTS & EMISSIONS FROM TREATMENT PR. TONNE WASTE TREATED ACCORDING TO ENVIRONMENTAL REPORT 2014 FROM SOIL RECOVERY A/S

Input or emission		Pr. tonne of waste	
Input	Electricity	kWh	164
	Diesel	l	1.01
Emissions factors			
Emissions to air from electricity	GHG	g/kWh	308
	SO_x	g/kWh	0.05
	NO_x	g/kWh	0.20
Emissions to air from diesel	GHG	g/kWh	1,411
	SO_x	g/kWh	0.09
	NO_x	g/kWh	0.96
Emissions to water	Sewage water	m^3/kWh	2.55
To landfill	Solids	Tonne/tonne	0.58

Use of chemicals on the rig

In the table below the division of the color coding of the chemicals are summarized.

TABLE: IMPORTED CHEMICALS TO THE RIG DIVIDED ON TYPES

Types of chemicals imported and used on the rig	Color code	Amount used during well construction, relative (%)
Viscosifier	Green / Yellow	3.1%
Biocides	Yellow	0.08%
pH control	Green	0.85%
Weighting. Gelling	Green	50.6%
Lost Circulation	Green	2.2%
Shale inhibitors	Green	1.1%
Emulsifiers	Yellow / red	1.9%
Dope	Yellow / black	0.01%
Cementing chemicals	Green / Yellow / red	7.7%
Completion fluids	Green	8.7%
Cleaning agent	Green / yellow	0.18%
Base oil	Yellow	22.5%
Other Chemicals	Yellow	1.1%

Appendix 3 Dilution calculations of soluble chemicals (PEC/PNEC)

Introduction

The present note forms part of the project "Natural capital accounting on the HA1 well in the Hejre Field carried out by COWI AS for Maersk Drilling.

The objective of this appendix is to determine the area and volume of the sea that is likely to be affected by discharge of different chemicals (planned and/or unintended) from the Hejre platform into the North Sea.

These data are used for estimating the environmental cost associated with permitted and unintended discharges during well construction.

Method

The method to be applied is based on the so-called "PEC/PNEC" model, see appendix to this appendix. The model calculates the ration between the Predicted Environmental Concentration (PEC) of a specific chemical substance in the environment and the Predicted No Effect Concentration (PNEC), at which marine organisms are at risk of being negatively affected. The distance where PEC/PNEC = 1 is the distance beyond which the risk is considered negligible ("no risk").

The PEC values are determined based on discharge quantifications and the oceanographic processes determining the dilution, drift and spreading. The basic theory behind these processes is described in terms of Gaussian dilution processes.

The PNEC values are based on eco-toxicological laboratory tests for each substance.

Results

Permitted discharge of chemicals during well construction

The following discharge events and chemicals are investigated:

TABLE: PERMITTED DISCHARGE DESCRIPTION IN TERMS OF CHEMICALS, DISCHARGE DURATION AND DISCHARGED MASS (FROM DONG). TRADENAMES ARE CONFIDENTIAL. INFORMATION FROM DONG

Start Date	End Date	Discharge duration (hrs.)	Chemical	Discharged to Sea (kg)
20-08-2014	21-08-2014	24.0	Chemical 1	79
07-10-2014	07-10-2014	1.0	Chemical 1	51
04-12-2014	04-12-2014	0.2	Chemical 1	426
27-11-2014	27-11-2014	7.8	Chemical 1	710
07-10-2014	07-10-2014	1.0	Chemical 2	40
04-12-2014	05-12-2014	24.0	Chemical 2	968
27-11-2014	27-11-2014	7.8	Chemical 2	951
04-12-2014	05-12-2014	24.0	Chemical 3	370
27-11-2014	27-11-2014	7.8	Chemical 3	579

All three chemicals selected for the assessment contain only one active chemical substance (rest is water); therefore no additive effects shall be taken into account. The ratio of active substance in the table below expresses the weight of active substance divided by the weight of product - rest is water.

TABLE: PNECS AND SUBSTANCE DATA FOR THE SELECTED CHEMICALS (BASED ON INFORMATION FROM HALLIBURTON, PERS. COMM., 2015)

Substance name	PNEC (mg/l)	Log Pow	Molecular weight	Degradation (28 days)	Amount of active substance (per amount product, rest is water)
Chemical 1	1.0	<0	>600	38%	60%
Chemical 2	1.0	-	>700	39%	30%
Chemical 3	3.64	-	>700	32%	60%

Permitted discharges - Assumptions

The following oceanographic assumptions are taken for conducting the PEC/PNEC calculations:

Current velocity: 0.05 m/s (middle water depth)

Water depth: 70 m

No degradation of the substance is included in order to make a conservative estimation of the affected area and volume.

Flux of substance:
For calculation reasons, the mass flow has to be expressed in terms of discharge and substance concentration. Therefore, a fictitious discharge Q of 1000 m^3/day (corresponding to approximately12 l/s) is introduced and is combined with the corresponding substance flux that will result in the given discharge concentration of substance. The list of observed discharged substances is given in the table above, which provides the duration and discharge rate. The concentrations are calculated for a fictive discharge of 1000 m^3/day. The observed events are used to describe events likely to occur.

Permitted discharges - Impact distances

Based on the above assumptions, PEC/PNEC calculations are performed. The concentration in the centerline, downstream of the discharge is illustrated in as example in the figure below:

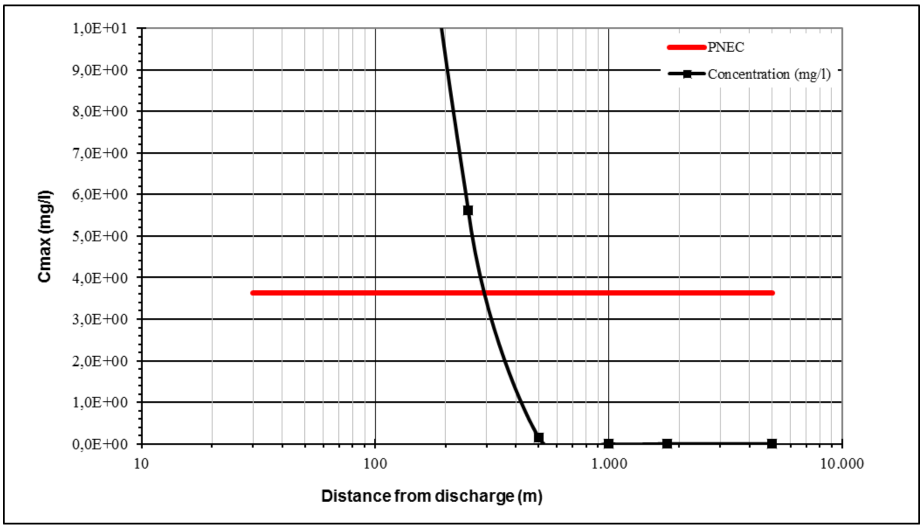


FIGURE 16-1: ILLUSTRATIVE EXAMPLE BASED ON FICTITIOUS DATA: CENTRELINE CONCENTRATION OF CHEMICAL 1 ON 6/12 2014 (BLACK LINE). THE PREDICTED NO EFFECT CONCENTRATION (PNEC) IS INDICATED WITH THE RED LINE.

Based on the calculations and the graphics the following distances, where the predicted environmental concentration is equal with the predicted no effect concentration PEC/PNEC = 1, distances and hence also areas and volumes of impact are found for each of the reported cases. Thus, in the above example the "no risk" distance is approximately 300 meters from the discharge point.

Permitted discharges - Impact volumes

The discharge will gradually spread with the current in a plume with increasing distance from the point of discharge. The plume will spread more horizontally than vertically, due to the different dispersion characteristics of the two dimensions in the ocean.

The width B of the plume at a distance x_1 from the point of discharge is given by:

$$B(x_1) = 2\sqrt{2\,D_2\frac{x_1}{U}}$$

Where:

D_2 is the dispersion coefficient in the horizontal and is expressed as
$D_2 = k \cdot U \cdot y$, where K is a constant, U is the current velocity in the ocean and y the water depth (k is 1.0 for coastal waters, k= 0.07 for oceanic surface waters, k= 0.035 for oceanic intermediate waters and k= 0.0175 for oceanic bottom water).

The height of the plume in the distance x1 from the point of discharge is given by

$$H(x_1) = 2\sqrt{2\, D_3 \frac{x_1}{U}}$$

Where:

D_3 is the vertical dispersion coefficient: $D_3 = k \cdot 0.004 \cdot U \cdot y$, where k, U and y are described above.

The affected horizontal area A is assumed to be triangular and described by the distance L and the width B at the endpoint of the plume:

$A = ½ \cdot L \cdot B$

If the plume volume is described as a cone, the volume V of the cone is given as:

$Vol = 1/3 \cdot \pi \cdot H \cdot B/4 \cdot x$

For the Hejre Field the following hydrographic parameters are chosen:

Water depth:
70 m
Discharge depth (approximately mid depth): 35 m
Current speed at discharge depth: 0.05 m/s

Based on the above figures, the distance of impact and the affected water volume are determined for each of the reported events. The results are presented in the table below:

TABLE: IMPACT DISTANCE AND IMPACTED WATER VOLUME. * DISTANCE WHERE PEC/PNEC = 1 I.E. THE "NO RISK" DISTANCE

Substance	Date of permitted discharge	Distance* (m)	Width (m)	Horizontal area (m^2)	Impacted water volume (m^3)
Chemical 1	20-08-2014	10	14	70	1
Chemical 1	07-10-2014	50	31	780	20
Chemical 1	04-12-2014	300	77	12,000	800
Chemical 1	27-11-2014	85	41	1,700	60
Chemical 2	07-10-2014	70	37	1,300	40
Chemical 2	04-12-2014	60	34	1,000	30
Chemical 2	27-11-2014	200	63	6,300	350
Chemical 3	04-12-2014	50	31	780	20
Chemical 3	27-11-2014	250	71	8,800	500

The average distance is 120 m, with a standard deviation of 103 m. The average water volume is 206 m^3, with a standard deviation of 285 m^3. Due to the small vertical dispersion in the ocean, the plume will be relative horizontal ("flat").

Thought experiment - Unintended discharge

Please keep in mind that the Thought experiments are not based on data from the Hejre Field, but are fictitious scenarios.

Unintended discharge - size considerations

Unintended discharges are included as Thought Experiments, allowing for a choice of number, type and size of unintended discharge to sea during the drilling operation. The assessment method applied is similar to the method used for calculating the affected areas following permitted discharge and is described in previous chapter.

From confidential registrations of unintended discharges from drilling activities on several rigs in the North Sea it is seen that unintended discharges often consist of chemicals, diesel fuel or hydraulic oil. Crude oil is rarely seen in unintended discharges.

For the purpose of the Thought Experiments unintended discharge sizes of 1, 15, 25 and 100 kg are addressed for the following types of assumed unintended discharge components:

- Yellow class chemical assumed similar to Chemical 1
- Red class chemical (fictitious substance with environmental characteristics similar to red class chemicals)
- Oil (diesel)

Color classes of chemicals are described in chapter 6.3. It is assumed that the unintended discharges are accidental and hence occur over a relatively short period of 0.1 hour (= 6 minutes).

The unintended discharges are assumed to spread at mid water depth and the current speed is set to 0.05 m/s. This is a conservative assumption since dispersion is larger in the upper layers of the ocean

Unintended discharge - Chemical of "yellow" class

In order to describe the effect of various unintended discharge volumes on horizontal area (affected distance and volume), the chemical 1 (from Group 2, see 0) is chosen for various unintended discharge volumes. The toxicity of substances from the "yellow" class is so weak that significant impact distances larger than 10 m are only found for unintended discharges larger than 100 kg. For illustration purpose, an unintended discharge range of the chosen yellow substance between 100 and 100,000 kg is chosen. The latter spill size may appear somewhat unrealistic. It is included, however, to illustrate the general mixing processes. The resulting relations are given below, note the log-log illustration.

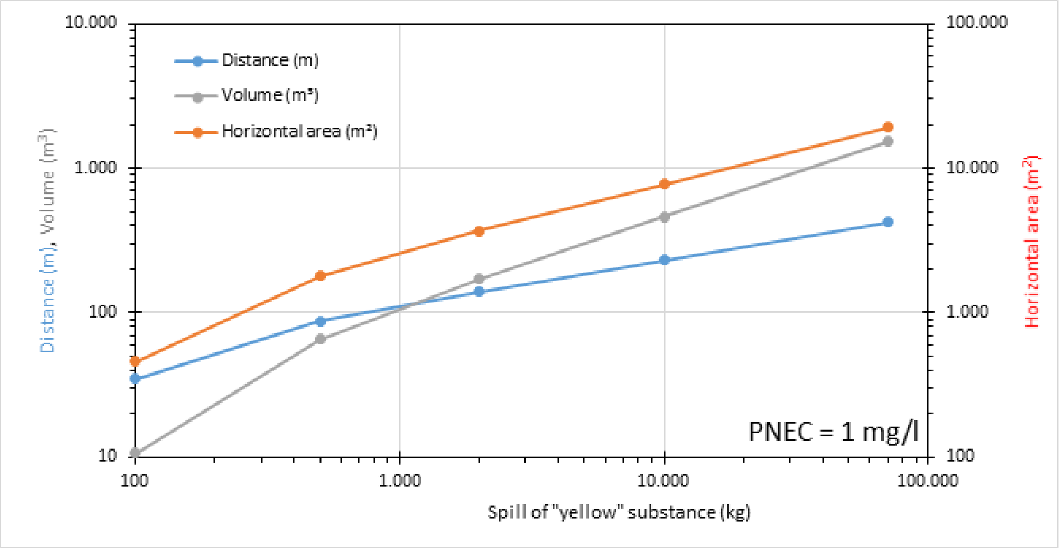


FIGURE: ILLUSTRATION OF "NO RISK" DISTANCE, HORIZONTAL AREA AND SEAWATER VOLUME AT DIFFERENT UNINTENDED DISCHARGES OF A REPRESENTATIVE "YELLOW" CHEMICAL.

The linear appearance in the log-log diagram illustrates the relatively large affected areas at small spill sizes.

For an unintended discharge interval between 1 and 100 kg, the effect is found to be smaller than the uncertainty, i.e. horizontal area smaller than 100m², distance smaller than 10 m and volume smaller than 1 m³.

Unintended discharge - Chemical of "red" class

In order to describe the effect of various unintended discharge masses on horizontal area (as well as on affected distance and volume), a fictitious "red" substance is chosen for various unintended discharge volumes. The PNEC value of 1 µg/l is chosen for toxic effect based on an LC50/EC50 = 1 mg/l and applying an assessment factor, AF = 1000 to derive the PNEC value.
The resulting relations are given below (note the log-Lin illustration).

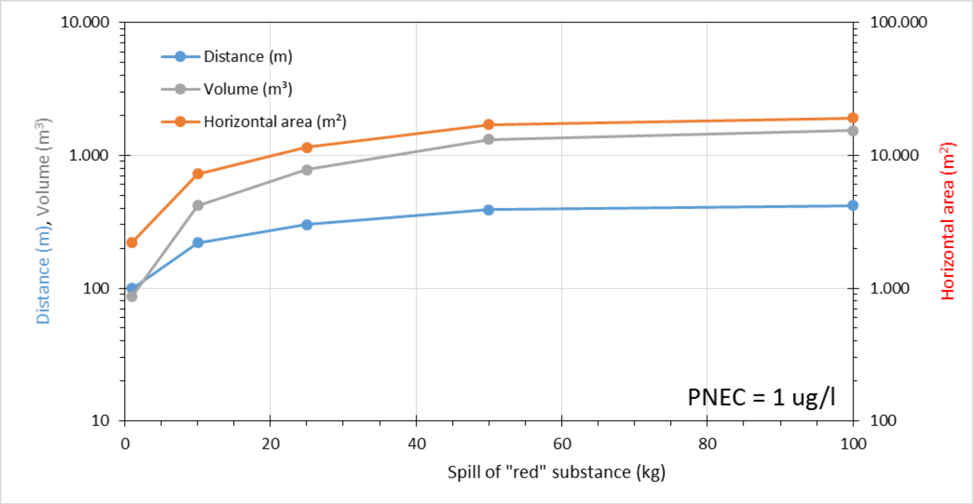


FIGURE: ILLUSTRATION OF "NO RISK" DISTANCE, HORIZONTAL AREA AND SEAWATER VOLUME AT DIFFERENT UNINTENDED DISCHARGE SIZES FOR A REPRESENTATIVE FICTITIOUS "RED" CHEMICAL WITH A PNEC VALUE OF 1 UG/L.

In order to illustrate the variability of model assumptions a red chemical with a PNEC value = 10 µg/l is used. This is the PNEC for acute toxic effects, which is derived from the LC50/EC50 by applying an acute AF = 100. I.E. this PNEC is only valid for short, not regularly recurring releases, i.e. unintended discharge s or similar taking place less than once per month on the average. The corresponding area, distances and volumes are given below.

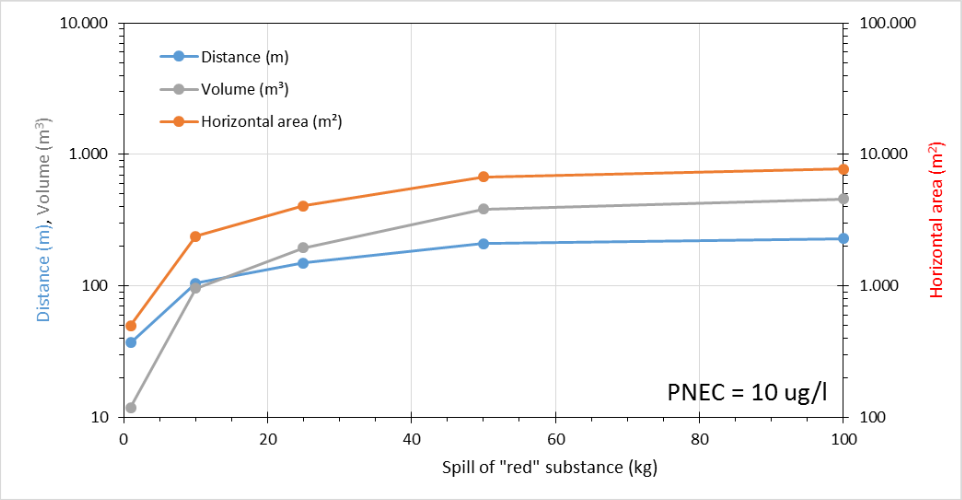


FIGURE: ILLUSTRATION OF "NO RISK"DISTANCE, HORIZONTAL AREA AND SEAWATER VOLUME AT DIFFERENT UNINTENDED DISCHARGE SIZES FOR A REPRESENTATIVE FICTITIOUS "RED" CHEMICAL WITH AN ACUTE PNEC VALUE OF 10 UG/L.

The above two cases are assumed to represent the expected result range due to choice of different "red" chemicals.

Unintended discharge - Oil: Diesel

In contrast to dissolvable chemicals, light oil products will stay on the water surface and will not mix with the water. Therefore, a PEC/PNEC analysis will not apply to oil. Many different oil types are at risk of being spilled accidentally from a drilling rig.

A sheen thickness will be of the scale of 0.0001 mm to 0.0003 mm (ITOPF, 2015 http://www.itopf.com/fileadmin/data/Documents/TIPS%20TAPS/TIP1AerialObservationofMarineOilSpills.pdf) for diesel oil. For thinner slicks the thickness is so small that the oil not is visible. Therefore, it is assumed that an unintended discharge with this thickness will not be harmful to the environment.

The diameter and the area of a circular unintended discharge are determined for the thickness of 0.1 nm and 0.3 nm, respectively.

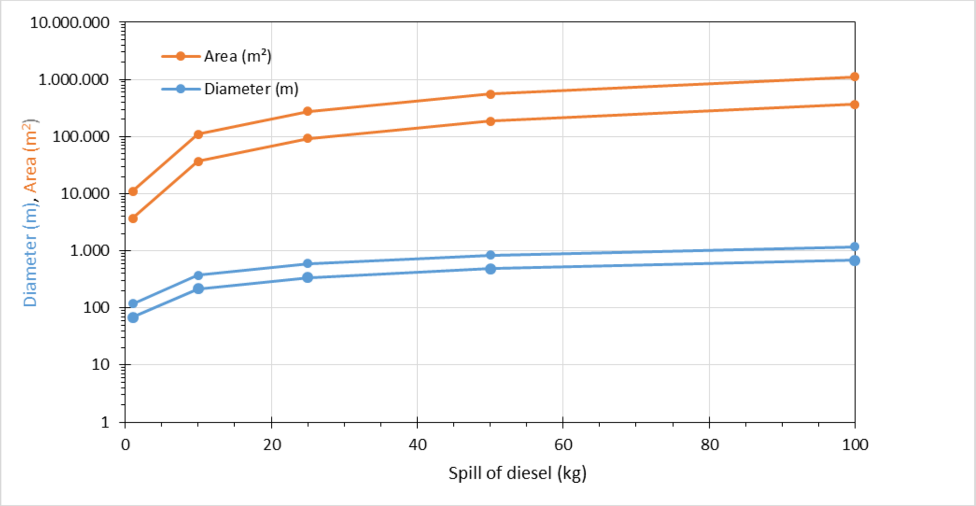


FIGURE: ILLUSTRATION OF AFFECTED DISTANCE AND HORIZONTAL AREA AT DIFFERENT SPILL MASSES AT TWO SPILL THICKNESS 0.0001 MM AND 0.0003 MM.

It is seen that the affected area is determined within a range of a factor 3, depending on the ultimate thickness of the unintended discharge.

If the unintended, i.e. instantaneous accidental discharge consists of diesel, is expected that the unintended discharge is evaporated with the time scale of 3-5 hours. For other and less volatile oil types with a density lower than the density of sea water the same affected areas and diameters will apply. The difference is that such oils will evaporate slower and to a smaller degree, in other words the slick will be more persistent.

Discussion – Permitted and unintended discharge

Permitted discharges

For the permitted discharge registration period with a duration approximately 5 months, 9 discharge events where reported for the 3 substances assessed in this technical note. The maximum water volume affected to a degree where a negative effect on marine organisms can be expected was about 800 m^3. The average area value was about 200 m^2.

It is found that the small discharges will result in relative large impacts whereas increasing spill volumes will increase the impact area/volume relatively less.

Unintended discharges

Please keep in mind that the Thought experiments are not based on data from the Hejre Field, but are fictitious scenarios. Please also note that no discharges of red or black chemicals have been reported for HA-1.

The calculations of impacts of accidental discharges for three fictitious substances are summarized below for two accidental discharge sizes of 10 kg, 25 kg and 100 kg as examples.

TABLE: OVERVIEW OF THE ESTIMATED IMPACTED AREAS FROM FICTITIOUS ACCIDENTAL DISCHARGES. DUE TO THE SIGNIFICANT VARIANCE OF THE INPUT PARAMETERS AND THE GENERAL UNCERTAINTY OF THE METHOD, THE RESULTS ARE TO BE UNDERSTOOD AS INTERVAL AND ORDERS OF MAGNITUDE.

Acc. discharges volume & type	**10 kg**			**25 kg**			**100 kg**		
	Area (m^2)	Length (m)	Volume (m^3)	Area (m^2)	Length (m)	Volume (m^3)	Area (m^2)	Length (m)	Volume (m^3)
Yellow chemical	<100	<10	<1	<100	<10	<1	<100	<10	<1
Red chemical (PNEC 1-10 ug/l)	2,400-7,200	105-220	100-420	4,000-12,000	150-300	200-800	8,000-20,000	230-420	500-1,500
Oil (thickness 0,1-0,3 nm)	37,000-110,000	220-380	NA	93,000-280,000	340-600	NA	370,000-1,200,000	690-1,200	NA

For discharged oil, the impacted volume is assessed to be so small that it is denoted as "NA" in the table above, since the oil is not likely to be dissolved in water under the slick to a considerable degree.

Due to the significant variance of the input parameters and the general uncertainty of the method, the results are to be understood as interval and orders of magnitude with due respect to the assumptions used

References

ITOPF, 2015:
http://www.itopf.com/fileadmin/data/Documents/TIPS%20TAPS/TIP1AerialObservationofMarineOilSpills.pdf

Methodology for calculations of PEC/PNEC ratios

The environmental impact assessment of chemicals and aqueous discharges or spills is based on the comparison of calculated Predicted Environmental Concentration (PEC) and Predicted No Effect Concentration (PNEC). When PEC is larger than PNEC, the concentration in the environment exceeds the concentration at which the chemical is considered not to exert any toxic effects. The model corresponds with CHARM project /Karman et al., 1996 and Thatcher et al., 2001/. Discharge specific chemical concentrations (C_w) are used in the model, which is more precise than using the generic calculation of C_w in CHARM.

The discharged chemicals may either stay in the water column or drop to the sediment on the seabed with settling particles. PEC and PNEC are, therefore, calculated for both water and sediment. Staying in the water column, the concentration of the chemical will decrease with time due to dilution, sedimentation and biodegradation. Once in the sediment, the concentration will depend on the partitioning of the chemical between sediment and water, and the chemical's potential for biodegradation.

By the use of the dilution model, the distance at which the chemical will impact the pelagic environment may be calculated. Due to the rapid dilution of the discharges, biodegradation in the water column is ignored.

The distance at which the chemical will impact the benthic environment is calculated under the assumption that the sedimenting particles settle evenly around the platform under the influence of a standard refreshment rate of the seawater. Biodegradation in the sediment is assumed to occur only approximately 10% of the time due to bioturbation of anaerobic marine sediments and resulting oxygen depletion.

The potential for bioaccumulation of discharged chemicals is assessed on the basis of information on bioconcentration factors (BCF) or octanol-water partition coefficients (P_{ow}). The potential for bioaccumulation is not quantified.

Calculation of PEC and PNEC

Calculation of PEC_{water} and $PNEC_{pelagic}$

PEC_{water} designates the predicted environmental concentration at a given distance from the point of discharge. In this assessment PEC_{water} is calculated for distances of 100 m; 250 m; 500 m; 1,000 m; 1,780 m and 5,000 m (1,780 m being the radius of a circle with the area of 10 km^2). Based on the maximum concentrations at these distances, a graph showing the concentration as a function of the distance is produced and the distance at which PEC_{water} equals $PNEC_{pelagic}$ is deducted.

PEC_{water} is calculated using the dilution model described later. This model is validated through field work carried out by scientific workers and is recognised through the last 15-20 years where COWI has used the model. The dilution model is more advanced than for instance the dilution model of CHARM.

$PNEC_{pelagic}$ is deducted from reported results of ecotoxicological tests and the application of assessment factors. The endpoint of the ecotoxicological tests is most commonly LC50 and EC50 values. LC50 values designate the concentration at which 50% of the tested organisms die, whereas EC50 values designate the concentration at which the tested parameter (e.g. growth rate, immobilisation) is inhibited by 50%. In order to predict the concentration, at which the chemical is not anticipated to cause adverse effects to the ecosystems, the ecotoxicological endpoint value is divided with an assessment factor. The size of the assessment factor depends on the amount and character of the data available for the assessment. Appendix Table 1 indicates the assessment factors applied. The assessment factor is applied to the lowest value available among the set of endpoints for the chemical.

Effect assessment of discharged products has been carried out under the assumption that the product can be defined by the properties of each of its compounds and the total toxicity of the product. Effect assessment of discharged products has been carried out for each non-PLONOR compound. The concentration of the compound in the product is often given as an interval. In these cases the assessments are made conservative: the lowest concentration is used for calculating toxicity (EC) and the highest concentration is used for calculating the water concentration (C_w).

APPENDIX TABLE 1: ASSESSMENT FACTORS FOR CONVERTING ECOTOXICOLOGICAL ENDPOINT DATA INTO PNEC

Assessment Factors		EC_{50} and LC_{50} values		
		At least data for algae, crustaceans **and** fish	Data but not for algae, crustaceans **and** fish	No data
NOEC values	At least data for algae, crustacean **and** fish	NOEC/10	NOEC/10	NOEC/10
	Data but not for algae, crustaceans **and** fish	NOEC/10 or EC_{50}/100	NOEC/10 or EC_{50}/1000	Not relevant
	No data	EC_{50}/100	EC_{50}/1000	No result

Calculation of $PEC_{sediment}$ and $PNEC_{benthic}$

$PEC_{sediment}$ is calculated using the following formulas:

$$PEC_{sediment} = C_w * D_{regional} * P_{sw} * (1-d_{sediment}) \qquad (1)$$

$$D_{regional} = \frac{\frac{F_w}{V_p}}{r + d_1} \qquad (2)$$

$$P_{sw} = f_{oc} * P_{ow} \qquad (3)$$

$$d_{sediment} = 1 - (1-d_1)^{36.5} \qquad (4)$$

$$d_1 = 1 - 10^{\frac{\log(1-d_{28})}{28}} \qquad (5)$$

In which:

C_w = Concentration of the chemical before discharge (mg/l)
$D_{regional}$ = Regional dilution factor
P_{sw} = Partition coefficient between sediment and water
$d_{sediment}$ = Degradation of a substance in the sediment after 1 year (fraction)
F_w = Volume of produced water discharged (m^3/day)
V_p = Volume of water per platform (m^3); standard platform area (10 km^2) * the depth at the satellite fields (60 m)
r = Refreshment of the seawater in the area around the platform; standard value: 0.24 day^{-1}
d_1 = 1 day biodegradation (fraction)
d_{28} = 28 day biodegradation (fraction)
f_{oc} = Fraction organic carbon in sediment (fraction of wet weight); standard value: 0.04
P_{ow} = Partition coefficient between octanol and water.

$PNEC_{benthic}$ may be calculated using ecotoxicological endpoint values for sediment reworking animals and applying the assessment factors presented, or by converting $PNEC_{pelagic}$ to $PNEC_{benthic}$ by the following formula:

$PNEC_{benthic} = P_{sw} * PNEC_{pelagic}$.

Dilution model

Introduction

This report describes the formulas used by COWI for calculating the dilution of wastewater discharged to the sea from platforms in the North Sea. This model has not been validated scientifically by COWI in the North Sea, but it is based on field work carried out by scientific workers and is recognized through the last 15-20 years where COWI has used this model in projects for municipalities and the industry in Denmark and abroad.

The formulas are valid for the case with no or only weak stratification in the sea. This means no or only small density differences between the surface water and the bottom water which is the normal situation at water depths up to about 40 m in the North Sea. Around the satellite fields, situated at 60 m depth, stratification may occur occasionally, and the dilution model will not be able to model transport across the stratification layer. However, this layer will act as a boundary for the plume to pass on to the section below the layer. Therefore, as a “worst case” description, the model is used with a standard depth of 40 m, assuming that a stratification layer will limit the mixing of the plume below 40 m.

The dilution of wastewater depends on many physical processes. Near to the outlet, i.e. in the so-called near field, the dilution is governed by the characteristics of the discharge: Outlet velocity, density, diameter, etc. Farther from the outlet, i.e. in the far field, the dilution is governed by the characteristics of the receiving water: Depth, current velocity, wind and waves, etc.

In sections 3.2 and 3.3, the dilution in the near field and in the far field is described.

In 3.4 the uncertainty in the dilution calculations is described.

The near field

In the near field momentum from the outlet and buoyancy phenomena dominate the dilution.

If the density of the wastewater equals that of the seawater there will be no buoyancy. In this case the discharge will form a pure jet governed by the outlet momentum.

With no outlet momentum, but a density difference between the wastewater and the seawater the discharge will form a pure plume. If the density of the waste water is lower or higher than the density of the sea water, the waste water will rise to the sea surface or fall down to the bottom of the sea.

If both momentum and buoyancy are present the discharge may be called either a jet or a plume, depending on the size of the so-called densimetric Froude number:

$$F_{\Delta} = \frac{V_o}{\sqrt{\Delta_o g D_o}} \qquad (2.1)$$

$$\Delta_O = \frac{\rho_a - \rho_0}{\rho_a} \qquad (2.2)$$

In which:

V_o: Outlet velocity (m/s)
Δ_o: Outlet density difference (no dimension)

g: Acceleration of gravity (= 9.81 m/sec^2)
D_o: Diameter of outlet (m)
ρ_a: Density of ambient water, i.e. seawater (kg/m^2)
ρ_o: Density of waste water (kg/m^3).

If F_Δ is greater than one, momentum dominates, and the discharge will act mostly as a jet. If F_Δ is less than one, the discharge will act mostly as a plume.

Normally, the initial dilution is interpreted as the dilution from the outlet to the sea surface or the sea bottom. If the outlet is a horizontal jet, the wastewater will spread horizontally. In this situation, an initial dilution cannot be defined.

The general equation describing the velocity and the dilution in the center axis for vertical jets and plumes are /Abraham, 1963/:

$$\frac{V_{\max}}{V_o} = 6.2\,\frac{D_o}{s}\left(1 + 0.33\left(\frac{s}{D_o F_\Delta}\right)^2\right)^{1/3} \qquad (2.3)$$

$$S_{\min} = 0.18\,\frac{s}{D_o}\left(1 + 0.22\left(\frac{s}{D_o F_\Delta}\right)^2\right)^{1/3} \qquad (2.4)$$

In which:

V_{max}: Maximum velocity, i.e. the centre axis velocity (m/s)
S_{min}: Minimum dilution, i.e. the centre axis dilution
s: Distance from outlet (m).

Equations similar to Eqs. 2.3 and 2.4 have been developed by others, e.g. /Cederwall, 1968/.

For pure jets, i.e. $F_\Delta \rightarrow \infty$, the Eqs. 2.3 and 2.4 reads:

$$\frac{V_{\max}}{V_o} = 6.2\,\frac{D_o}{s} \qquad (2.5)$$

$$S_{\min} = 0.18\,\frac{s}{D_o} \qquad (2.6)$$

These equations are valid for all directions of jets, i.e. including horizontal and vertical jets. Instead of the constant 0.18 /Fisher, 1979/ proposes 0.20.

With no outlet momentum, i.e. $F_\Delta \rightarrow 0$, the Eqs. 2.3 and 2.4 describe the pure plume situation:

$$\frac{V_{\max}}{V_o} = 4.3\,F_\Delta^{-2/3}\left(\frac{s}{D_o}\right)^{-1/3} \qquad (2.7)$$

$$S_{\min} = 0.109\,F_\Delta^{-2/3}\left(\frac{s}{D_o}\right)^{5/3} \qquad (2.8)$$

Instead of the constant 0.109, /Fisher, 1979/ proposes 0.129.

If the outlet is horizontal, Eqs. 2.5 and 2.6 may be used for jets as explained above. For plumes, the following simple equation may be used /Liseth, 1977/:

$$S_{\min} = \frac{2}{3}\,\frac{s}{D_o} \qquad (2.9)$$

This equation is valid for s/D_oF_Δ greater than one and less than 20. Outside this range, graphical solutions may be used, see e.g. /Liseth, 1977/.

For jets the mean dilution will be between 1.4 and 2.0 times the minimum dilution. This range may also be used for plumes as a reasonable approximation.

The maximum concentration in the centre axis is the reciprocal of the minimum dilution. If the wastewater is diluted before it is discharged to the sea, the maximum concentration is:

$$C_{\max} = \frac{C_o}{S_{\min}} \qquad (2.10)$$

In which C_o: Concentration of matter in outlet water.

The far field

By an analogy to molecular diffusion, see e.g. /Fisher, 1979/, the dispersion of wastewater in the far field it is assumed to follow Fick's Law. This law states that the mass of waste crossing a unit area per unit time in a given direction is proportional to the gradient of waste concentration in that direction.

Using Fick's Law the one-dimensional equation describing the dispersion in case of no convection is:

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} \qquad (3.1)$$

In which

C: Concentration, i.e. volume waste water to volume seawater (m^3/m^3)
t: Time (sec.)
x: Coordinate (m)
D: Dispersion coefficient (m^2/sec.)

The term dispersion describes the combined dispersal owing to turbulent diffusion and spatial velocity variations. In the ocean there will often be a velocity variation between top and bottom, leading to different velocities of wastewater between top and bottom. The result will be a larger mixing than in the case of no spatial velocity variations.

In the one-dimensional case, if all waste to time t = 0 is placed in the plane x = 0, the solution to Eq. 3.1 is, see e.g. /Engelund, 1968/:

$$C = \frac{1}{2\sqrt{\pi D t}} \exp\left(-\frac{x^2}{4Dt}\right) \qquad (3.2)$$

This equation equals the well-known Gaussian equation, if

$$\sigma^2 = 2Dt \qquad (3.3)$$

in which σ^2: Variance (m^2)

In the far field the wastewater follows the mean current in the sea. Calling the horizontal coordinate in the current direction x_1, the mean velocity of the sea current is:

$$U = \frac{x_1}{t} \qquad (3.4)$$

In the two-dimensional case (plume), in case of a steady outflow of waste to the sea the transport of waste is:

$$Q_o = U \int_{\infty}^{\infty} \int_{\infty}^{\infty} C\,(x_1,\ x_2,\ x_3,)\ dx_2\, dx_3 \qquad (3.5)$$

in which:

Q_o: Waste water transport (m^3/sec.)
x_1: Horizontal coordinate in the flow direction (m)
x_2: Horizontal coordinate lateral to the flow direction (m)
x_3: Vertical coordinate lateral to the flow direction (m).

Assuming Gaussian concentration profiles, i.e. using Fick's Law we have:

$$C(x_1, x_2, x_3) = C(x_1, 0, 0)\ \exp\left\{ -\frac{x_2^2}{2\sigma_2^2} - \frac{x_2^3}{2\sigma_2^3} \right\} \qquad (3.6)$$

For the Gaussian distribution the following equation is valid:

$$\int_{\infty}^{\infty} \frac{1}{\sqrt{2\pi}}\ \exp\left(-\frac{x^2}{2} \right) dx = 1 \qquad (3.7)$$

Inserting Eq. 3.7 in Eqs. 3.6 and 3.5 yields:

$$Q_o = UC\,(x_1, 0, 0)\, 2\pi\, \sigma_2 \sigma_3 \qquad (3.8)$$

C (x_1, 0, 0) is the concentration at the centre line of the plume, i.e. the maximum concentration. The reciprocal of this value is the minimum dilution:

$$S_{\min} = \frac{2\pi U\, \sigma_2 \sigma_3}{Q_0} \qquad (3.9)$$

If the wastewater is discharged at the surface or near the bottom, mixing from the top or the bottom of the plume is impossible. In this case, the dilution is only 50%:

$$S_{\min} = \frac{\pi U\, \sigma_2 \sigma_3}{Q_o} \qquad (3.10)$$

Using Eqs. 3.3 and 3.4 in Eq. 3.10 we get:

$$S_{\min} = \frac{\pi U}{Q_o} \sqrt{2 D_2 \frac{x_1}{U}} \bullet \sqrt{2 D_3 \frac{x_1}{U}} \qquad (3.11)$$

Or:

$$S_{\min} = K\, \frac{U x_1 y}{Q_o} \qquad (3.12)$$

In which y: Depth of water (m) and K: Constant defined by:

$$K = \frac{2\pi \sqrt{D_2 D_3}}{yU} \qquad (3.13)$$

The length scale of the vertical fluctuations is considerably smaller than for the horizontal fluctuations. For this reason, the vertical dispersion coefficient, D_3, is much smaller than the horizontal coefficient, D_2.

Field experiments have shown, see e.g. /Koh and Fan, 1970/, that D_3 depends on the vertical density gradient. In relatively shallow waters, i.e. depths less than about 40 m, the density gradient is normally small. This means that in the Danish sector of the North Sea, the influence of density gradients may be neglected.

In coastal waters, the following dispersion coefficients may be applied /Odgaard, 1976/:

$$D_2 = Uy \qquad (3.14)$$

$$D_3 = 0.004\ Uy \qquad (3.15)$$

In the ocean, D_2 and D_3 will be smaller than in coastal waters, especially due to smaller spatial velocity variations. To take care of this, a reduction constant, k, is introduced:

$$D_2 = k\ Uy \qquad (3.16)$$

$$D_3 = k\ 0.004\ Uy \qquad (3.17)$$

The following values of k are used:

Coastal waters:	k = 1.0
Ocean, surface layer:	k = 0.07
Ocean, medium layer:	k = 0.035
Ocean, bottom layer:	k = 0.0175

If, as an example, the water depth is 40 m and the velocity of the ocean current is 0.1 m/sec., the dispersion coefficients in the surface layer are:

$D_2 = 0.28\ m^2/sec.$

$D_3 = 0.001\ m^2/sec.$

In /Schroeder, 1976/ the following ranges are given:

$D_2 = 0.01 - 1\ m^2/sec.$

$D_3 = 0.0001 - 0.01\ m^2/sec.$

It is seen that the values based on Eqs. 3.16 and 3.17 are in the middle of the range.

Inserting the constants k in Eqs. 3.13, 3.16 and 3.17 gives the following results:

Coastal waters:	K = 0.40
Ocean, surface layer:	K = 0.028
Ocean, medium layer:	K = 0.028
Ocean, bottom layer:	K = 0.007

For the medium layer, k = 0.035 has been used, and mixing from both top and bottom of the plume. For this reason there is no difference between the surface and the medium layers.

The corresponding plume dilution equations may be established using the above given values for K and Eq. 3.12:

Coastal waters:

$$S_{\min} = 0.4\ \frac{U x_1 y}{Q_o} \qquad (3.18)$$

Ocean, surface layer and medium layer:

$$S_{\min} = 0.028\ \frac{U x_1 y}{Q_o} \qquad (3.19)$$

Ocean, bottom layer:

$$S_{\min} = 0.007\ \frac{U x_1 y}{Q_o} \qquad (3.20)$$

In case of a single puff-discharge, i.e. a momentary outlet, there will be mixing in the direction of the current as well. The dispersion coefficient in this direction, D_1 is an order of magnitude larger than D_2, i.e.:

$$D_1 = k\ 10\ U\ y \qquad (3.21)$$

The dilution equation corresponding to Eq. 3.10 reads:

$$S_{\min} = \frac{\pi\sqrt{2\pi}\ \sigma_1\sigma_2\sigma_3}{V_o} \qquad (3.22)$$

In which

V_o = Total volume of waste discharge (m^3).

Using the same principles as for the plume we get:

Coastal waters: $$S_{\min} = 4.45\ \frac{(yx_1)^{3/2}}{V_o} \qquad (3.23)$$

Ocean, surface layer: $$S_{\min} = 0.082\ \frac{(yx_1)^{3/2}}{V_o} \qquad (3.24)$$

Ocean, medium layer: $$S_{\min} = 0.058\ \frac{(yx_1)^{3/2}}{V_o} \qquad (3.25)$$

Ocean, bottom layer: $$S_{\min} = 0.010\ \frac{(yx_1)^{3/2}}{V_o} \qquad (3.26)$$

The constant K for the surface layer differs from the constant K for the medium layer. The reason is that K in the puff case depends non-linearly on k, while in the plume case there is a linear dependence.

The PUFF model: If the discharge is neither a plume nor a jet, COWI's PUFF model may be used. This model uses a series of puffs, simulating a discharge limited in time. Each puff is treated as a single puff and the resulting concentration is obtained by superposing these single puffs.

The sea current in the Danish sector has been measured by DHI /DHI, 82-85/.

The typical velocity in the bottom layer is 0.1 - 0.2 m/sec. and in the surface layer 0.1 - 0.3 m/sec.

As conservative values the following velocities normally have been used by COWI:

Surface and medium layer: 0.08 m/sec.
Bottom layer: 0.05 m/sec.

Other velocities may be used, for instance an actual distribution of velocities at a given site (e.g. a current rose). This may be used to establish several dilution lines, each representing a given fraction of the time in which the dilution will be greater (or smaller) than indicated by the line.

Uncertainty

The concentrations in the sea estimated by the formulas presented in chapters 2 and 3 are encumbered by uncertainties, e.g. due to fluctuations in the discharge and variations in the sea current.

To take care of such uncertainties, either conservative parameters or uncertainty factors (UF) may be used.

In the calculations performed by COWI, both concepts are used as will be explained in this chapter.

Furthermore, reference will be made to the methods used for onshore industries, illustrated by the considerations carried out in connection with the discharge of waste water from Junckers Industrier /VKI, 1991/ and /Miljøstyrelsen, 1992/.

The concept of uncertainty factors is described in these three references.

The basic idea is that the concentration of a given toxic matter in the environment (the sea) shall be less than the concentration with no effects on the environment:

$$\frac{NEC}{C} > 1 \qquad (4.1)$$

In which:

NEC: No effect concentration (theoretic)

C: Concentration in the environment (theoretic)

If NEC and C are assessed using a limited or an uncertain knowledge - which is the normal situation - uncertainty factors (UF) may be introduced. By definition these factors are greater than one, and we have:

$$\frac{NEC}{C} = \frac{NOEC / UF_{NOEC}}{PEC \bullet UF_{PEC}} > 1 \qquad (4.2)$$

Or

$$\frac{NOEC}{PEC} > 1 \bullet UF_{NOEC} \bullet UF_{PEC} \qquad (4.3)$$

In which:

NOEC: No observed effect concentration
PEC: Predicted environmental concentration, e.g. based on the formulas in chapters 2 and 3
UF_{NOEC}: Uncertainty factor, NOEC
UF_{PEC}: Uncertainty factor, PEC.

The greater the uncertainty is, the greater the UF should be.

In this report dealing with dilution, only UF_{PEC} will be treated. The analysis is based on the formulas described in chapters 2 and 3.

Referring to /VKI, 1991/ the uncertainty factor UF_{PEC} mainly depends on:

- Variation in the waste water discharge
- Uncertainty in the data and in the calculation of the dilution in the sea.

The variation in the discharge rate of toxic matter, m_o, is included in the uncertainty factor UF_{NEC}, see /VKI, 1991/.

This means that m_o may be understood as a fixed parameter when dealing with UF_{PEC}, while the discharge rate of wastewater may fluctuate.

Normally, the discharge rate of toxic matter is small compared to the discharge rate of wastewater. For this reason the concentration in the outlet is:

$$C_o = \frac{m_o}{Q_o} \qquad (4.4)$$

In which:

m_o: Discharge rate of toxic matter (m^3/sec)

Q_o: Discharge rate of wastewater (m^3/sec).

In case of a continuous discharge, combination of Eqs. 4.4, 2.6, 2.9, 3.19 and 3.20 yields:

$$\text{Near field: } PEC = \frac{C_o}{S_{\min}} = \frac{m_o D_o}{Q_o k_n s} \qquad (4.5)$$

$$\text{Far field: } PEC = \frac{C_o}{S_{\min}} = \frac{m_o}{K_F U x_1 y} \qquad (4.6)$$

The constant k_N is 0.18 or 2/3 and the constant K_F is 0.028 or 0.007, as described in chapters 2 and 3.

In case of a momentary discharge, an analysis similar to the following analysis for the continuous discharge may be carried out.

The discharge rate of toxic matter, m_o, may with regard to PEC be understood as a fixed value as explained above. Furthermore, the outlet diameter, D_o, and the distance from the outlet, s or x_1, may be regarded as well-known parameters without uncertainties.

Therefore, dealing with the near field dilution, the only parameters encumbered by uncertainties are Q_o and k_N.

In the near field, e.g. just after the termination of the initial dilution, acute effects are most important. This means that the concentration considered should correspond to peak values modified due to equalization before the outlet, e.g. in the tanks of the treatment plant.

From Eq. 4.5 it is seen that a low Q_o results in a high concentration. /VKI, 1991/ proposes the use of the 95% fractile of the discharge flow (in the "low" end).

This concept of using conservative (i.e. small) wastewater flows has been used by COWI too.

The constant k_N is well documented and with only a small uncertainty.

Far field

The PEC in the far field used for the discharge from Junckers Industrier is the mean concentration from top to bottom, i.e. corresponding to full mixing in the entire water column.
The dilution equation used by COWI, Eq. 4.6, does not describe the mean, but the maximum concentration. For this reason no UF_{PEC} is needed.
The influence of currents etc. has for the discharge from Junckers Industrier been treated by using data yielding the maximum concentration in a four-day-period, i.e. the concept of conservative parameters. This is in accordance with COWI's use of a small sea current, 0.05-0.08 m/sec.

In the far field, i.e. hundreds of meters from the outlet, chronic effects are most important. This is the reason why a relatively long period of four days has been used for the discharge from Junckers Industrier.

In the far field formula, Eq. 4.6, the size of K_F, y and U influence the result. U has been discussed above.

The depth of sea, y, should in principle be without uncertainty. However, in case of a stratified sea (density differences between surface and bottom layers), the depth y is only the depth of the layer in which the spreading occurs. The estimation of this depth may in some cases be uncertain. Normally, there will be no stratification, and here y is the depth of the sea, i.e. without uncertainty.

The constant K_F may be encumbered by a considerable uncertainty. However, the transformation of dispersion coefficients from coastal waters to the open sea, see Eqs. 3.16 and 3.17, using the constant k is rather conservative: A factor greater than 10 for the surface layer and a factor greater than 50 for the bottom layer.

The use of these conservative transformations shows that there is no need for uncertainty factors.

Thus, the formulas used by COWI and the way they are used does not raise a need for the introduction neither of additional uncertainty factors, UF_{PEC}, nor more conservative parameters.

The principles and concepts used are in accordance with the principles and concepts used for onshore industries, e.g. for the discharge from Junckers Industrier.

References

/Abraham, 1963/	Abraham, G., "Jet Diffusion in Stagnant Ambient Fluid", Delft Hydraulics Laboratory. Publication No. 29, 1963
/Cederwall, 1969/	Cederwall, K., "Hydraulics of Marine Waste Water Disposal", Report No. 42, Hydraulic Division, Chalmers Institute of Technology, Göteborg, 1968
/DHI, 82-85/	Gorm Field Environmental and Structural Monitoring System, DHI for Mærsk Olie og Gas A/S, 1982, 1984 and 1985
/Engelund, 1968/	Engelund, F.A. "Hydrodynamik", Den private Ingeniørfond, DTH, 1968
/Fisher, 1979/	Fisher, H.B. et al, "Mixing in Inland and Coastal Waters", Academic Press, 1979
/Karman et al., 1996/	Karman C.C. et al, "CHARM III Main Report", TNO-MEP-R96/355, TNO Institute of Environmental Sciences, The Netherlands.
/Koh and Fan, 1970/	Koh, R.C.I, and Fan, L.N., "Mathematical Models for the Prediction of Temperature Distributions Resulting from the Discharge of Heated Water in large Bodies of Water", EPA Water Pollution Control Research Series 16140 DWO, 1970
/Liseth, 1977/	Liseth, P. "Dykket utslipp i resipient", PRA-rapport nr. 14, Oslo, 1977
/Miljøstyrelsen, 1992/	"Økotoksikologisk vurdering af industrispildevand", Miljøprojekt nr. 188, Miljøstyrelsen, 1992.
/Odgaard, 1976/	Odgaard, J., "Analytical Dilution Models", Lectures in Environmental Hydraulics, WHO, 1976
/Schroeder, 1976/	Schroeder, H., "Coastal Hydraulics", Lectures in Environmental Hydraulics, WHO, 1976.
/Thatcher et al, 2001/	Thatcher et al. "A CIN revised CHARM III Report 2001. User guide for the evaluation of chemicals used and discharged offshore", Version 1.2. 12 July 2001.
/VKI, 1991/	"Kravfastsættelse til industrispildevand, Junckers Industriers cellulosefabrik", Vandkvalitetsinstituttet, juni 1991.

To be filled in

Appendix 4 LCA approach

Introduction

Maersk and DONG has initiated a project to assess the NCA methodology for the drilling of the HA-1 well in the Hejre Field.

This report focuses on the potential environmental aspects from cradle to the site in Esbjerg by using the LCA approach and methodology.

An attributional LCA is applicable for this purpose due to the fact that the focus in this project is to describe the environmentally relevant physical flows to and from a product or process. As opposed to attributional LCA is consequential assessment which describes how relevant environmental flows will change in response to possible decisions.

Furthermore, attributional LCA focuses just on historical impacts over a products entire life.

Production of steel and other materials are expected to be included in the current production capacity – thus no production changes need to take place to meet the demands of Maersk Drilling regarding materials supply.

Based on these arguments, it is decided to apply attributional LCA for this project.

Scope

The scope of the LCA is from extraction of raw materials (grave) to the delivery of the materials at the site in Esbjerg.

The transport from Esbjerg to the rig is included in a separate calculation for vessels. The estimated life time of the wells is 30 years.

Packaging is not included in the study.

Transport

The transport is described in this section.

Only the transport by truck and ship to the harbour in Esbjerg is included.

Transport of materials (e.g. oil) in pipes is not included in the assessment.

Truck

Transportation by truck is performed in diesel powered trucks.

Two types of trucks have been used:

- Truck with a total capacity of 40 tonnes and 24.7 tonnes payload
- Truck with a total capacity of 26 tonnes and 17.3 tonnes payload

A fixed standard utilisation of the trucks at 85% is applied (based on an assumption incorporated into the LCA data in the Ecoinvent v3.1 database).

Transport distances by trucks are based on data from Google Maps. It is assumed, that all materials/products from Europe are transported 2,500 km by road (eg. from Spain, the southern part of Italy etc.).

The fuel is transported 240 km from Kalundborg to Esbjerg by truck.

Ship

The transport of raw materials from the extraction site to the production site is assumed to take place with a bulk carrier.

It is also assumed that the raw materials are extracted in China and transported to Europe – a trip on 14,000 km.

The LCA data from the GaBi database has been developed on a basis where the load capacity is 3,000 tonnes and a capacity utilisation of 48 %.

Transport of fuel

The fuel is transported as raw oil on pipelines from the North Sea to the harbour in Fredericia.

In Fredericia, the raw oil is then divided into several end products including diesel.

Lastly the fuel is transported to Esbjerg by truck.

Effect factors

The effect factors quantifies the potential environmental impacts into CO_2-equivalents for global warming, N- and NO_X-equivalents for marine eutrophication, SO_X-equivalents for terrestrial acidification, particulate matter formation (PM2.5-equivalents), black carbon (a fraction of the CO_2-equivalents) and lastly water depletion (m^3).

Data

The effect factors for the calculations are extracted from the LCA software GaBi Professional and the Swiss LCA database Ecoinvent v3.1.

The LCA methodology, ReCiPe, is applied.

Where data is available, an average of 2 or 3 datasets is applied (e.g. one dataset from PE International and another dataset from Ecoinvent v3.1). This ensures that the data and results are robust, as the level of the chosen data is verified by comparing to similar data for the same products/raw materials used.

Regarding the selection of LCA datasets great effort has been made to choose the data that fits the best with the consumed products and raw materials, E.g. when carbon steel is used for the well, the average of two LCA datasets for carbon steel has been identified in the LCA database to represent the actual consumption. As steel types and thus content of various metals are numerous and all steel types are not represented in the LCA database, is has been necessary to identify and use the LCA data which represent the actually used steel as best as possible. Whether the selected LCA data give rise to higher or lower calculated potential environmental impacts compared to the theoretically correct and precise description of the actually used products and raw materials are not known.

Conservative assumptions are applied – e.g. using the maximum possible content of polymer (when water is the other substance available in the product).

Steel

To assess the potential environmental impacts from steel, data from PE International is used.

The split of potential environmental effects into phases the LCA report derive from the World Steel Association[17] publication about LCA.

Here it is indicated that the split between the life cycle stages for greenhouse gasses and energy is:

- 98% of the potential environmental impacts occur in the raw materials stage
- The remaining 2% occurs in the production stage

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[17] The World Steel Association: Life Cycle Assessment Methodology report. 2011.

It is assumed that the other effect categories (eutrophication etc.) also occur according to this split.

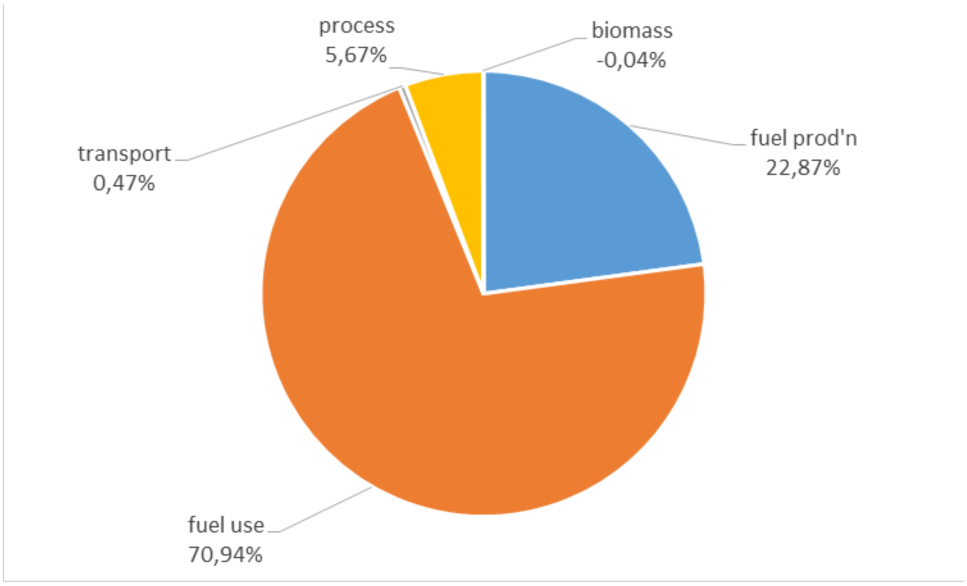
Chemicals

Water in the chemicals is not included in the calculation- thus only the content of various plastics are included in the LCA calculation.

For LCA data on plastic PE International and Ecoinvent v3.1 is used.

The split of potential environmental effects into phases the LCA report derive from PlasticsEuropes publication on Eco-profiles for plastics[18].

Here it is indicated that the split between the life cycle stages for greenhouse gasses and energy is:



APPENDIX FIGURE 1: EMISSION OF GREENHOUSE GASSES DURING THE LIFE CYCLE OF PLASTIC.

Thus the indicated fuel use and fuel production (fuel prod'n) must be allocated to the raw materials extraction. The process energy and derived emission of greenhouse gasses is for the production of plastic based on the oil products produced by the raw materials producer.

The only phase missing in the above figure is the production of chemicals for Maersk where plastic types are used as an ingredient. Based on the data from PlasticsEurope it is assumed that the potential environmental impacts can be split into the following fractions:

- 93,8% of the potential environmental impacts occur in the raw materials stage (until the plastic reaches the producers of the specific chemicals for Maersk)
- 5,7% occurs in the production stage of the chemicals
- The remaining impacts is allocated for transport

It is assumed that the other effect categories (eutrophication etc.) also follow this split.

Cementitious products

For cement data from Ecoinvent v3.1 and PE International is used.

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[18] PlasticsEurope. Eco-profiles of the European Plastics Industry. Liquid Epoxy Resins. March 2005.

The extraction of raw materials and the production of cement take place at the same company.

The production of chemicals for Maersk where cementitious products are used as an ingredient is produced by Haliburton.

Based on the assumptions for the chemicals, it is assumed, that the main emissions occur where the cement is produced. The split applied is:

- 98% of the potential environmental impacts occur in the raw materials stage and the production of cementitious products
- The remaining 2% occurs in the production stage (Haliburton)

It is assumed that the other effect categories (eutrophication etc.) also follow according to this split.

Fuel

For fuel data from PE International is used.

As plastics are made from oil and oil is used for the production of fuel, the data presented in section 5.2 can be used.

Here it is indicated that the split between the life cycle stages for greenhouse gasses and energy is:

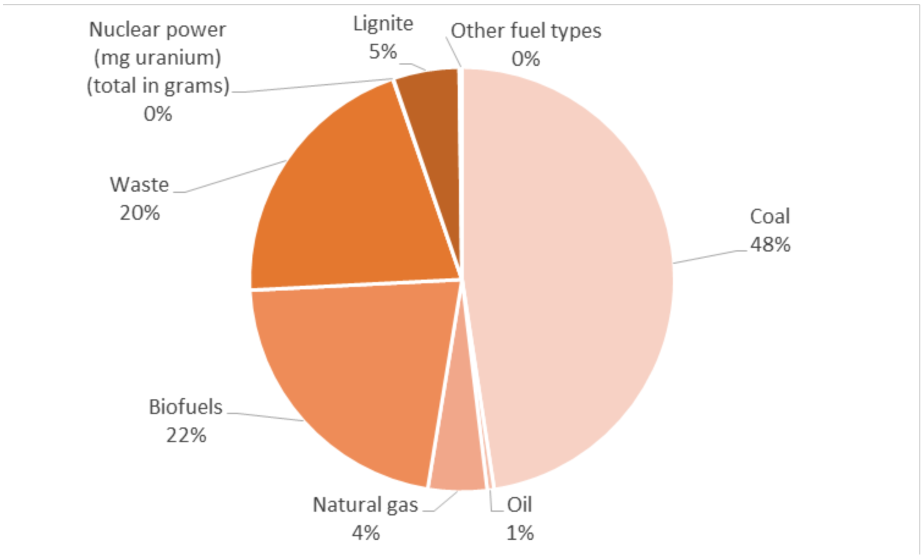
- 70,94% of the potential environmental impacts occur in the raw materials stage
- 22,87% occurs in the production stage of the fuel

It is assumed that the other effect categories (eutrophication etc.) also follow this split.

Electricity

The LCA data for electricity is derived from energinet.dk.

According to their registrations, the distribution of fuel types in Denmark is:



APPENDIX FIGURE 2: FUEL TYPES TO GENERATE ELECTRICITY IN DENMARK IN 2014 (ENERGINET.DK)

On the basis of this distribution of fuel types, energinet.dk has calculated emission factors for 1 kWh electricity produced in Denmark.

The emission factors are:

LCA factor	Electricity ex. distribution	Distribution of electricity	Unit
Global warming	288	16	g CO_2-eq.
Marine eutrophication	0.19	0.01	kg NOx-eq.
Terrestrial acidification	5,00E-02	0,00E+00	kg SO2-eq.
Particulate matter formation	1.00E-02	0.00E+00	kg PM2.5-eq.
Black carbon	78.5	4.4	g C

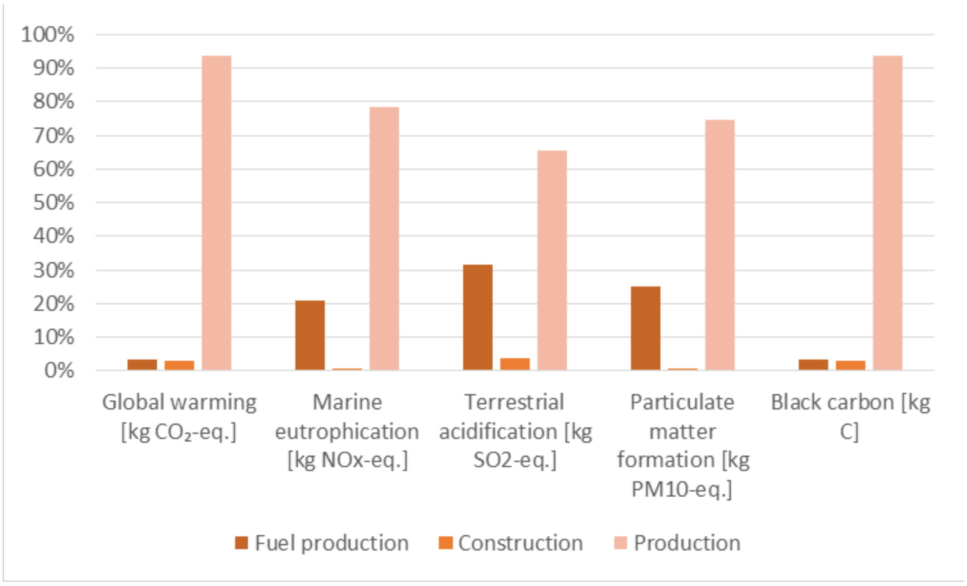
APPENDIX FIGURE 3: EMISSION FACTORS FOR THE PRODUCTION OF 1 KWH ELECTRICITY IN DENMARK

Energinet.dk has not published data for the water usage and emission of black carbon during electricity production.

The data for black carbon has been calculated on the basis of the molar weights of CO_2 and C. The molar relation is 12/44.

As the emission factors must be distributed into phases (raw materials extraction, transport, production etc.), the LCA background report from energinet.dk has been used (Livscyklusvurdering. Dansk el og kraftvarme. April 2010).

From this report the distribution between the single phases is:



APPENDIX FIGURE 4: DISTRIBUTION OF EMISSIONS IN EVERY PHASE OF ELECTRICITY

As it can be seen in the figure, the emission is not distributed evenly for all the effect factors. Thus the fuel production and the construction are of minor importance for the global warming potential and the black carbon. For the marine eutrophication, terrestrial acidification and particulate matter formation, the fuel production is of larger importance (approximately 20% to30% of the total potential environmental impacts).

[Text]

Development of advanced environmental reporting

Formålet rapporten er, at beskrive udviklingen og pilottest af en NCA tilgang, som dækker etableringen af offshore olie- og gasbrønden Hejre HA-1. Der anvendes data fra opstart til færdiggørelse af brønden samt fokuseres på samfundsmæssige omkostninger, som følge af miljøpåvirkninger i hele værdikæden ved at se på luftemissioner og udledninger til vandmiljøet.

The objective of the report is to describe the development and pilot test of an NCA approach covering the construction of the offshore Hejre HA-1 production well using data from start-up to completion and focusing on societal costs in the full value chain from environmental impacts on air and water.

The Danish Environmental
Protection Agency
Strandgade 29
DK-1401 Copenhagen K

www.mst.dk