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Life Cycle Assessment of Wastewater Treatment for Oil and Gas Operations

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MASTER THESIS

for

Student Anne Lise Torp

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Life cycle assessment of wastewater treatment for oil and gas operations

Livsløpsvurdering av avfallsvannbehandling for olje- og gassoperasjoner

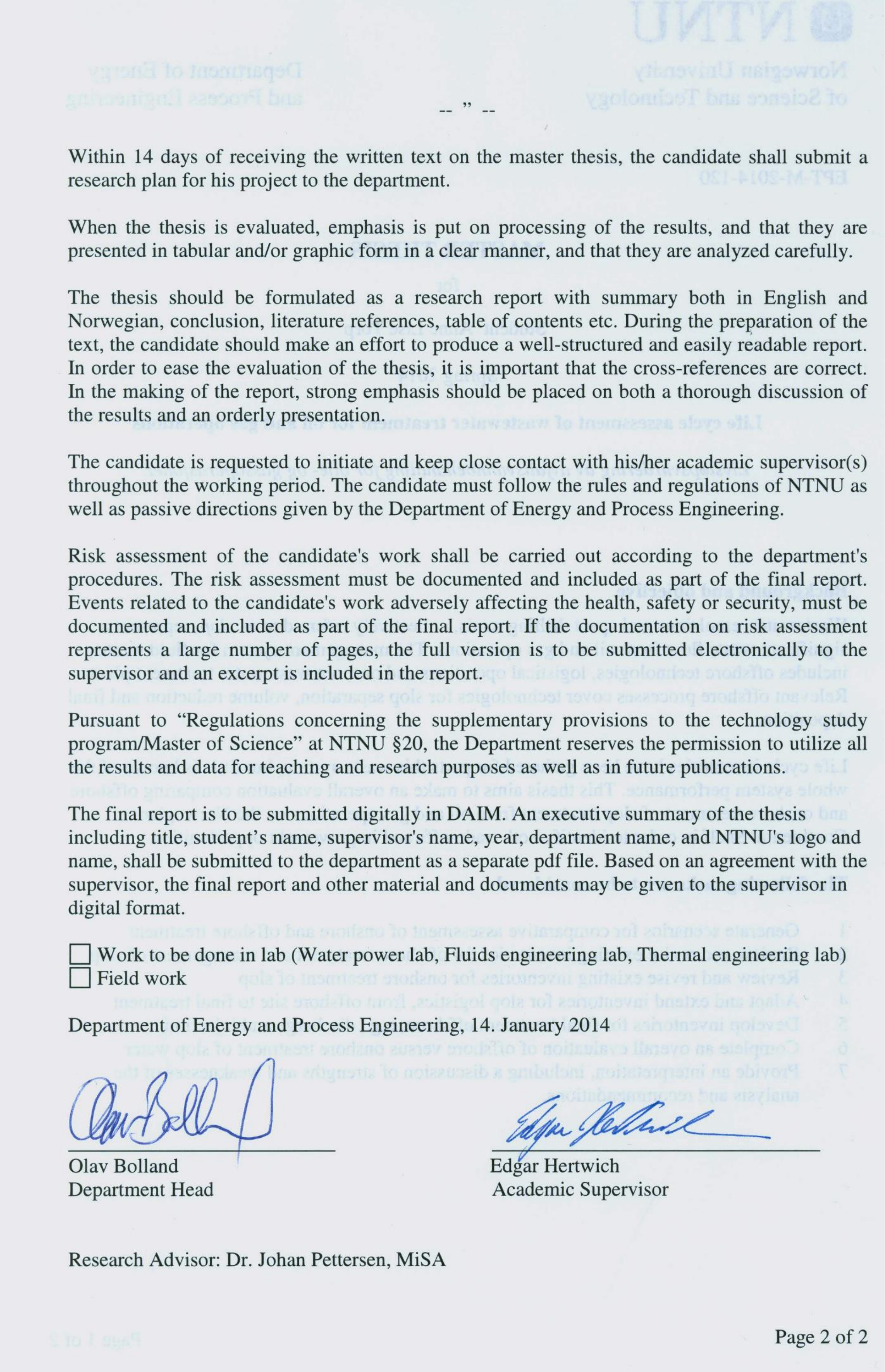
Background and objective

Wastewater, emulsions and spent drilling muds, collectively referred to as *slop*, represent a significant waste flow from oil and gas operations. The management system for fluid wastes includes offshore technologies, logistical operations and onshore wastewater treatment plants. Relevant offshore processes cover technologies for slop separation, volume reduction and final deposition.

Life cycle inventories have been gathered for parts this waste system, but little is known of the whole system performance. This thesis aims to make an overall evaluation comparing offshore and onshore treatment of slop treatment from oil and gas operations on the Norwegian Continental Shelf in order to identify both trade-offs and improvement opportunities.

The following tasks are to be considered:

1 Generate scenarios for comparative assessment of onshore and offshore treatment
2 Review and revise existing inventories for offshore treatment and management of slop
3 Review and revise existing inventories for onshore treatment of slop
4 Adapt and extend inventories for slop logistics, from offshore site to final treatment
5 Develop inventories for final treatment offshore; e.g., discharge and injection
6 Complete an overall evaluation of offshore versus onshore treatment of slop water
7 Provide an interpretation, including a discussion of strengths and weaknesses of the analysis and recommendations.



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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

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The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student’s name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 14. January 2014

Olav Bolland
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Edgar Hertwich
Academic Supervisor

Research Advisor: Dr. Johan Pettersen, MiSA

PREFACE

This thesis is the finalisation of my Master of Science degree in energy and environment at the department of Energy and Process engineering at the Norwegian University of Science and Technology (NTNU). This thesis is a collaboration between NTNU and MISA, and I have therefore had the privilege of utilizing the MISA offices and the wisdom found there, of which I am very thankful for.

There are several people that have helped me through this thesis, supporting me either academically or emotionally. I would like to express endless gratitude to my family and my boyfriend for always cheering me on, and instilling confidence in me. I am grateful for the support of all my friends, providing me with an outlet from the hardships of writing this thesis. Thank you Marthe Pande-Rolfsen for proofreading, and to my supervisor Edgar Hertwich for his input. Special thanks goes to my co-supervisor Johan Pettersen at MISA for his enthusiasm and guidance, inspiring me through my whole last year at university.

Anne Lise Torp

Trondheim, June 2014

ABSTRACT

Fossil fuel currently supply the majority of the world’s energy demand, and the demand is predicted to grow rapidly for the next decades. In order to meet this surging energy demand, drilling for oil and gas will escalate. This drilling activity produces slop water, a hazardous fluid waste, which cannot be directly discharged without treatment. Slop water is included in the zero-discharge policy for oil and other harmful chemicals that threaten the environment, issued by the government in 1997. Presently, there are three main scenarios for treating slop water: injection, onshore treatment and offshore treatment.

In this thesis, a comparison of the three different approached to slop treatment is conducted on the basis of their LCA performance. The injection scenario included drilling an injection well, operating the injection pump and the plug and abandonment of the well. The onshore scenario consists of transportation to the facility, four different treatment technologies and disposal. Offshore treatment features a simplified treatment on the rig, transportation of residue sludge to onshore facility where this undergoes end-treatment and disposal.

The results show that injection is the least favourable option because of the huge impacts the operation of the drilling rig brings to the scenario. Offshore treatment shows the most promising environmental performance, and the onshore is the intermediate scenario. The determining aspects of the impacts of the scenarios are the use of transport and fossil fuels and the ability to recover oil from the waste. The offshore scenario combines these factors in the most environmentally friendly way; lesser need for transport due to volume reductions by primary treatment and oil recovery.

A sensitivity analysis was conducted, presenting alternative power supplies and drilling fluids. This analysis showed that en electrification of the rigs will further benefit the offshore treatment’s performance and that the onshore treatments performance is at its best when supplied with a Norwegian electricity mix, as opposed to a European mix. In the injection scenario, the choice of drilling fluid is crucial for the final impact of the whole scenario. A water based mud with an as low a concentration of additives as possible is preferred.

The results of this study can aid in the discussion of which treatment of slop is the best and if the industry is heading in the right direction. It also provides insight into which processes in the system create the potential impacts and sensitive parameters.

SAMMENDRAG

Fossilt brensel leverer storparten av verdens energibehov i dag, og etterspørselen er spådd å vokse raskt de neste tiårene. For å møte dette økende energibehovet, vil boringen etter olje og gass eskalere. Boringen av brønner produserer slopvann, et farlig væskeavfall, som ikke kan slippes ut i havet uten behandling. Slopvann er inkludert i null-utslipps politikken for olje og andre skadelige kjemikalier som truer miljøet, utstedt av myndighetene i 1997. Det finnes tre hovedscenarier for behandling av slopvann: injeksjon, behandling på land og behandling offshore.

I denne avhandlingen er det gjennomført en sammenligning av de tre forskjellige slopvanns behandlingene på grunnlag av deres LCA ytelse. Injeksjons scenariet inkluderer boring av en injeksjonsbrønn, drift av innsprøytingspumpen og plugging av brønnen. Det landbaserte scenariet består av transport av slopvann til anlegget, fire ulike renseteknologier og avfallsdeponering. Offshore behandlings scenariet har først en forenklet behandling på riggen, transport av det resulterende slammet til et landanlegg hvor det gjennomgår en sluttbehandling og avfallsdeponering.

Resultatene viser at injeksjon er det minst gunstige alternativet på grunn av de store konsekvensene driften av boreriggen har på miljøet. Offshore behandling viser de mest lovende resultatene, og behandling på land er det mellomliggende scenariet. De avgjørende aspektene i scenariene er anvendelse av transport, fossile brennstoffer og evne til å utvinne olje fra avfallet. Offshore scenariet kombinerer disse faktorene på den mest miljøvennlige måten; mindre behov for transport på grunn av volumreduksjoner etter primærbehandling og oljeresirkulering.

En sensitivitetsanalyse ble gjennomført som presentere alternative strømforsyninger og borevæsker. Denne analysen viser at en elektrifisering av riggene på norsk sokkel vil bidra til at offshore behandling blir enda mer miljøvennlig og at den landbaserte behandlingen er på sitt mest miljøvennlige når den forsynes med en norsk elektrisitetsmiks, i motsetning til en europeisk miks. Under drillingen av injeksjonsbrønnen er valget av borevæske avgjørende for den endelige miljøpåvirkningen til hele injeksjonsscenariet. En vannbasert borevæske med en lav konsentrasjon av tilsetninger er å foretrekke.

Resultatene av denne avhandlingen kan være et innspill i diskusjonen om hvilken behandling av slopvann som er den beste, og gi en pekepinn på om bransjen er på vei i riktig retning. Avhandlingen gir også innsikt i hvilke prosesser i systemet skaper de største miljøkonsekvensene og hvilke parametere som er avgjørende for miljøavtrykket.

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ABBREVIATIONS

BTEX - Benzene, toluene, ethylbenzene, and xylenes
COD – Chemical oxygen demand
DAF – Dissolved air flotation
GHG – Greenhouse gas
HVDC – High voltage, direct current
ILCD – International reference life cycle data system
LCA – Life cycle assessment
LCI – Life cycle inventory
NCS – Norwegian continental shelf
NOGA – Norwegian oil and gas association
NPD – Norwegian petroleum directorate
OBM – Oil based mud
PAH – Polycyclic aromatic hydrocarbons
ROP – Rate of penetration
S.G. – Specific gravity
SBM – Synthetic based mud
TCC – Thermomechanical cuttings cleaner
TOC – Total organic carbon
VOC – Volatile organic compound
WBM – Water based mud

1 INTRODUCTION

The world is currently experiencing a clash between the ambitions of humans and the limits of nature. Anthropogenic pollution is at an all-time high and affects our ecosystems, whether it is through climate change or release of toxins. This damaging behaviour creates complex problems for our society, altering our way of life. It is vital to understand how and where pollution occurs, and to use this knowledge to better the situation.

Ever since the industrial age up to today, several different fossil fuels have been used for energy purposes. The use of fossil fuels is a major contributor to anthropogenic pollution, in all its life stages. Today oil and gas are one of the energy pillars of our society, and our economy. Norway is the largest oil producer in Europe, besides Russia, and the world's third largest gas exporter. The production of petroleum takes place in the North Sea and as with any type of production, it produces waste.

Slop water is an example of hazardous waste produced in the extraction of oil and gas, and represents a significant waste flow. This type of waste is under strict regulations from the government, including a zero-discharge policy that was implemented in 1997 on the Norwegian continental shelf. This means that the waste needs to be treated, and there are several ways to do so. Which is the best, seen from an environmental perspective?

1.1 OBJECTIVE AND SCOPE

The objective and goal of this thesis is to assess the environmental performance of slop water treatment technologies. The method of life cycle assessment was chosen for this comparative study because it includes all the repercussions that the waste treatments have both upstream and downstream, which gives a broader perspective on the environmental performance of each of the technologies.

There are three leading ways of treating slop water; injection into formation, onshore treatment and offshore treatment. Injection is simply done by pumping slop down a well and into a suitable underground formation. Both onshore and offshore treatment requires several processing steps before the treated water can be discharged. Because the offshore treatment does not include the whole processing chain, transportation of the slop from the offshore rig to an onshore treatment facility is needed in both cases. These three technologies will be studied in a LCA. The results of this analysis will be presented, compared and performance evaluated. Areas of mitigation will also be pointed out.

The aim of this study is to make a representative and correct model of the whole system performance of the three technologies, by combining and expanding life cycle inventories for parts of the waste system and creating inventories for the missing processes.

1.2 TASKS

During the course of this study, several different tasks were completed in order to get to the final product:

1. Generate treatment scenarios for comparative assessment.
2. Review, revise and expand inventory of offshore slop treatment constructed by Anthony Okiemute.
3. Review and revise inventory for onshore treatment constructed by myself, in the fall of 2013.
4. Construct inventory for injecting slop.
5. Build compete systems depicting the three different scenarios.

1.3 STRUCTURE OF THESIS

Chapter 2 starts with exploring the definition of slop water, where it comes from, how it affects the environment and the regulative framework of the waste. In chapter 3 the different scenarios of treatment are presented, including explanations of processes included in the treatment. Following this is the theoretical framework of the LCA methodology and how it is used in this study. Next is the inventory chapter, which tells the reader how the model is build up and its content. Subsequent are the results of the impact calculations based on the model and a sensitivity analysis testing the robustness of the model. Interpretation of the results and a discussion of them and their trade-offs are found in chapter 8. Conclusions drawn from the study and options for further work is given in chapter 9.

1.4 OVERVIEW OF EXISTING LITERATURE

There are numerous LCAs performed on solid waste treatment, municipal waste and of wastewater treatment in general. Less so for the waste from the oil and gas industry, but there are several articles concerning the different technologies used to treat it and how to meet the discharge criteria. Drill cuttings and produced water are wastes from oil production that have received more attention than slop water. Cuttings are solid material from the well coated in drilling fluid and produced water is formation water in the oil or gas reservoir. Slop water on the other hand is a by-product of the drilling of a well. There is only one LCA on the treatment of produced water published (Vlasopoulos et al., 2006), and there is a sore need for the subject of slop treatment to be explored, since it is a huge economic concern for the operators of drilling rigs and of environmental concern for everybody else.

2 BACKGROUND

This chapter explores the definition of slop water, where it comes from and what it contains. Explanations of how it affects the environment and the rules and regulations surrounding the treatment of this waste is also presented here.

2.1 INTRODUCTION

The petroleum offshore industry has been active on the Norwegian Continental Shelf for more than 40 years. Today there are just over 500 fixed oil and gas producing facilities situated on the NCS. The number of wells connected to each offshore installation varies greatly, from a few to several hundred. In total, about 5359 exploration and development wells have been drilled on the NCS since the first exploration well on the Balder field in the North Sea in 1966 (NPD, 2014). This drilling activity makes it possible to reach the oil and gas deposits in the submarine formations, but they also generate some waste, slop water being one of them.

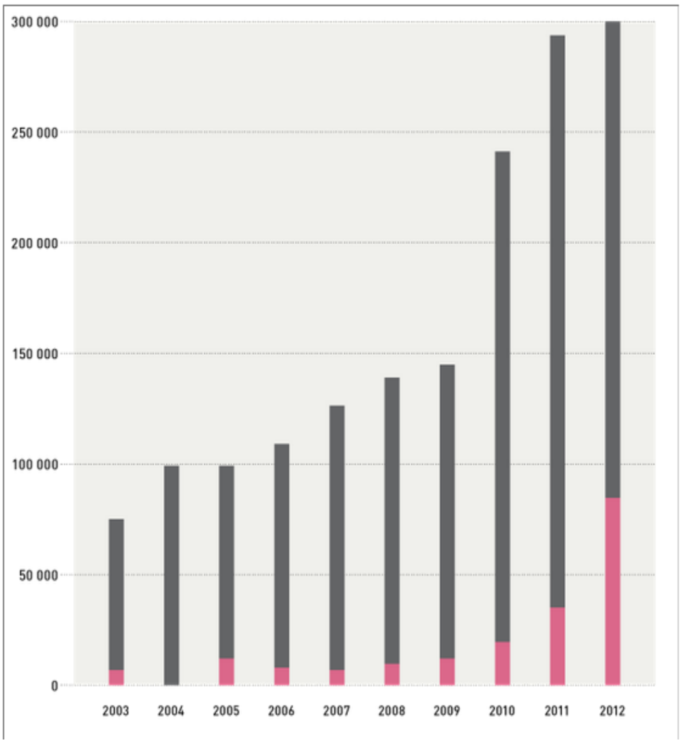

FIGURE 2.1: STATISTICS OVER THE DRILLING WASTE SENT TO SHORE FROM 2003 TO 2010 IN TONNES. CUTTINGS AND MUD IN BLACK AND SLOP WATER IN PINK . IT IS POSSIBLE THAT THE SLOP PORTION IN REALITY IS LARGER BECAUSE OF CLASSIFICATION ISSUES (NORSK OLJE OG GASS, 2013).

The amount of drilling waste sent to shore have been steadily increasing each year since the beginning of the 2000»s, with a jump in 2010-2012 because of failing injection wells, as figure 2.1 shows. The message to receive is one of caution against disregarding the importance of choosing the right way of treating this waste stream.

The oil benefits society in providing energy, but every stage in its life cycle can cause harmful effects on our environment and on ourselves. With the ever increasing demand for energy and the oil deposits on the NCS dwindling, the industry reports that they need to drill even more to maintain current levels of production (Sivertsen, 2011). Consequentially the increasing amount of waste from offshore drilling operations needs to be properly treated and disposed of, in the most environmentally friendly manner. To get the complete picture of the impacts associated with treating this waste, all the indirect impacts from the processes in the life cycle of treatment needs to be included. LCA is a good tool for doing just that.

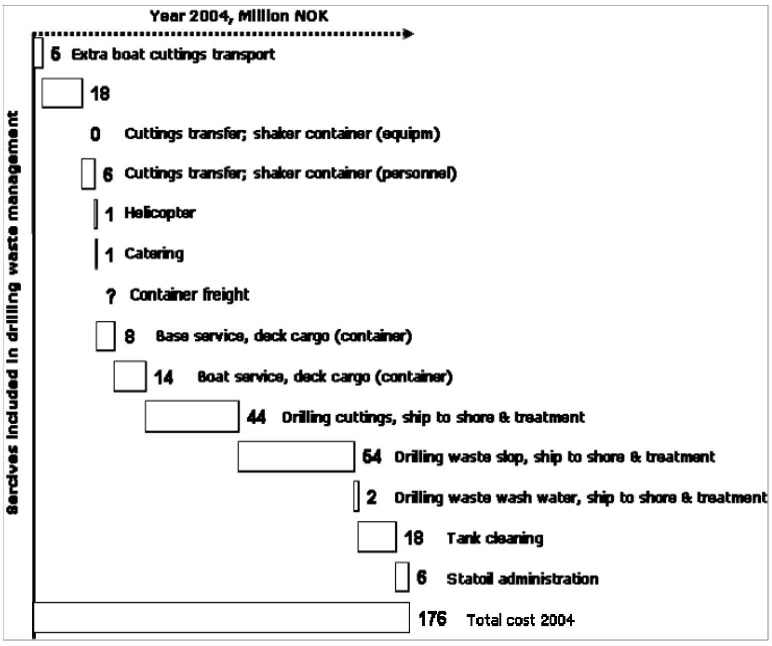

FIGURE 2.2: TOTAL COST OF OWNERSHIP FOR DRILLING FLUID HANDLING AND DISPOSAL AT STATOIL, 2004

An internal study in 2004 at Statoil uncovered the total cost of ownership for drilling waste handling and disposal divided across the different processes. The cost associated with drilling waste handling is not only limited to the costs of disposal, but includes different means of transportation, manpower and equipment. The largest part of the costs is, however the treatment of drilling waste. Largest of all the post is the treatment of slop water (Paulsen et al., 2006).

2.2 SLOP WATER DEFINITION

Slop water is a waste product resulting from the drilling of oil wells. Slop is made out of mostly water, oil, a plethora of other toxic agents and dissolved solids, minerals and metals. The pollutants found in the slop that require treatment include oil, grease, totally dissolved solids, boron as well as heavy metals. Slop is a collective term for several different water-oil mixtures because the chemicals in it and the concentrations they appear in, vary dramatically from platform to platform and site to site. This is one of the reasons why the treatment of slop water can be a challenge, because it has to be tailor-made for each source. An average estimate of the composition of slop is about 10% oil, 10% solids and 80% water (UiS et al., 2013). These percentages can vary greatly according to the operation and location of the rig, the type of well being drilled, type of drilling fluid used and how it is stored.

The volume of drilling slop produced per rig on a daily basis can vary from 15 m^3 to 100 m^3 depending on the rig, location and how it is operated (Dixit et al., 2010). Drilling with OBM often generates large quantities of slop compared to other types of drilling mud such as WBM (Water Based Mud) or SBM (Synthetic Based Mud). This drilling mud cools down the drill itself, carries out cuttings and sustains hydrostatic pressure to ensure that no formation fluid enters the bore well (James et al., 2002).

When drilling mud comes in contact with water, it takes the drilling fluid out of specification and the result is called slop mud. Slop mud can contain 50-90% water and 10-50% drilling fluids and is typically stored in tanks, separate from the slop water which has a higher water content, but it is also common to mix the two in the same tank. This is where classification of the waste is an issue, since slop can fall into many different categories.

The American Petroleum institute states that the oil in slop water appears in three different forms, free oil, emulsified oil and dissolved oil (Al-Ani, 2012). All of them have a different degree of emulsification and different ways of removing them. Free oil is the oil that we usually see at the surface of the water, as large flakes of oil. This oil consists of droplets larger than 20 microns and clearly makes up a distinct phase. An emulsion is defined as liquid droplets suspended in another liquid, homogenously dispersed throughout the carrier liquid (Turnkey-solutions.inc). Dissolved oil is where the oil is no longer in droplets, but a part of the water. The two latter forms cannot be removed mechanically, therefore other measures must be taken to remove them, such as biological or chemical treatment. The oily part of the slop can be engine lubricants, compressor lubricants, hydraulic oil, diesel, oily mud additives and crude oil (Snavely et al., 1983). This makes the slop water a hazardous waste and cannot be released directly back into the ocean. It has to be collected and treated, onshore, offshore or re-injected into a formation through a well.

There are similarities between the wastes called slop water and produced water. They undergo many of the same treatment steps before discharge, but are not produced in the same way. Produced water is a by-product of oil and gas production and is pumped up from a reservoir alongside the petroleum. The produced water comes from an underground formation and can contain several more toxic compounds than slop and even radioactive particles. Slop water is produced during drilling operations and not production, and is not as large a volume-stream.

Misinterpretation of the rather unclear classifications for the different waste types and little cohesiveness between the classification system and how things work in the industry have caused the Norwegian Environmental Agency to reassess the classifications. In 2012 Klif, The Norwegian Environmental agency, released the new terms of classification:

TABLE 2.1: OLD AND NEW CLASSIFICATIONS FOR WASTE FROM OFFSHORE OPERATIONS

Old Classifications		**New Classifications (with the corresponding old classification)**	
7041	Mineral oil based drilling mud	**7025**	Waste containing or contaminated with crude oil or condensate (7022/7030)
7030	Oil emulsions and slop water	**7031**	Emulsions containing oil, from the drilling deck (7030)
7022	Oil contaminated material	**7142**	Oil based drilling mud (7141)
		7143	Cuttings containing oil based drilling mud (7141)
		7144	Water based drilling mud containing hazardous chemicals (7141)

Uncertainty regarding the different classifications of waste has caused an underreporting of the amount of slop produced the last years, predominantly before the new and more stringent classifications, because slop could be categorised under 7025, 7031 and even mixed with 7142, and it was reported as something else than slop (Dahl-Hansen et al., 2012). This reflects the difficulties of reporting correctly to the authorities and to clearly state what the slop contains and to differentiate it from the other types of waste. To further complicate matters, slop water is often mixed with other types of waste like cuttings and oily drilling fluid. This praxis is a result of lack of room for storing them separately. The consequences of this practice is that the definition of slop is a broad and loose one, that the treatment of it must be individually catered to each batch of slop and that the size and importance of slop treatment may be underestimated.

2.3 WHAT MAKES SLOP HARMFUL TO THE ENVIRONMENT

Slop water consists of mostly water, but it also contains several substances that are harmful to the environment, such as aliphatic hydrocarbons, heavy aromatic compounds (PAH), alkylated phenols and heavy metals (Knudsen et al., 2004). That is why slop water cannot be discharged into the sea without treatment. In the oily part of the slop water, we find most of the harmful substances. Separating this part from the water removes a large portion of the harmful substances and the oil itself, which is a risk for sea birds, reefs and coastal lands especially. Other hazardous substances found elsewhere in the slop are H2S and CO2 as they are corrosive gases (Epstein et al., 2002).

The metals of most concern in drilling discharges are (Neff, 2002 #4).

- Barium, Ba
- Cadmium, Ca
- Chromium, Cr
- Copper, Cu
- Lead, Pb
- Mercury, Hg
- Zinc, Zn

Some of the metals are necessary for normal development in animals (Cu, Cr and Zn), while the others have no known biological function (Ba, Cd, Hg and Pb), and are toxic at even low concentrations. Metal pollution in any biological system is hazardous due to carcinogenic and oxidative potential (Valavanidis et al., 2010). Mercury is a neurotoxin to humans and exposure leads to heart problems, birth defects and serious neurological disorders (Minimata disease). Bioaccumulation in marine ecosystems are a topic of great concern considering that heavy metal contamination of fish is an increasing route of human exposure (Epstein and Selber, 2002).

Polycyclic aromatic hydrocarbons (PAH) are hydrocarbons containing two or three fused aromatic rings and are a component of petroleum. This type of hydrocarbon is especially toxic, it has a high persistence in a marine environment and is a major contributor to the pollution of marine sediment (Neff, 2002, Ruus et al., 2009). Contaminants in discharges to sea will often disperse rapidly and spread over large distances and ultimately end up in sediments (Bjørgesæter, 2008). Studies have shown that PAH can mimic hormones, causing effects in development and reproductivity in both humans and wildlife (Epstein and Selber, 2002).

The marine ecosystem relies on the nutrition in the sediment for its smallest organisms, benthos and it is an environmental marker. Figure 2.2 describes how the pollutants from discharge travels, bio-accumulates and magnifies in the marine ecosystem all the way up to primary predators and the fish that we eat. Fishery stocks risk reduction due to higher mortality rates and threaten fishing communities. Mortality in seals, sea otters, turtles and whales can be due to oil pollution (Boesch et al., 1987).Since the methods of disposal of drilling waste and the waste itself varies, it is difficult to quantify precisely the impact they have on the ecosystem.

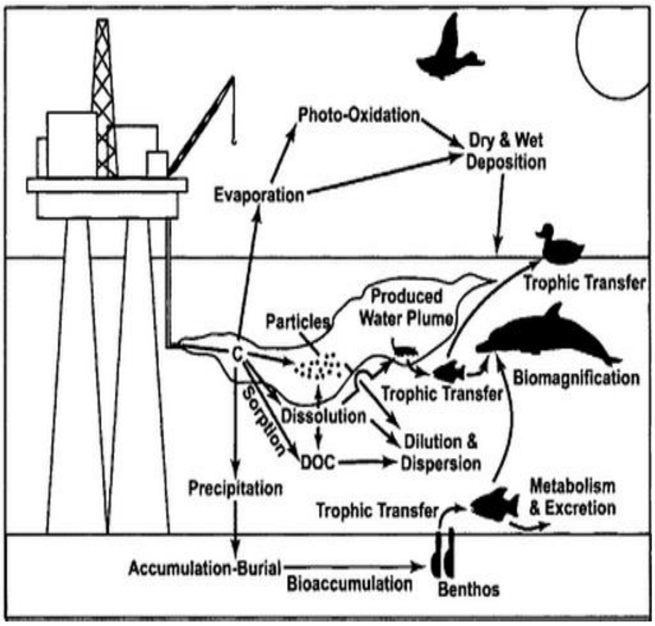

FIGURE 2.3: FATES OF CHEMICALS DISCHARGED TO SEA (NEFF 2002)

Drilling operations on the NCS account for most of the pollution that affects the marine sediments. Figure 2.3 shows the majority of the chemical discharge from Norwegian petroleum activities comes from drilling. Over 90% of these discharges are “green chemicals” and regarded to present little or no risk to marine organisms. It is the chemicals graded as yellow, red and black that pose a real threat and needs to be phased out.

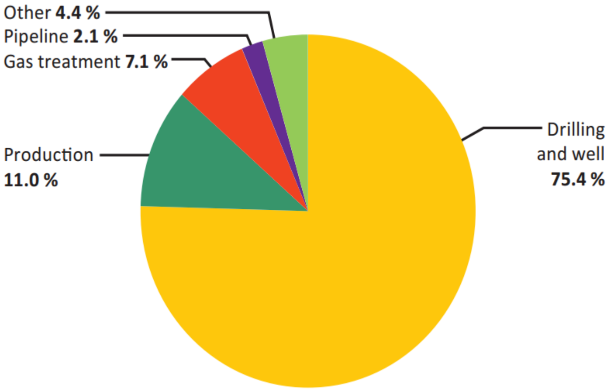

FIGURE 2.4: STATISTICS OVER DISCHARGE OF CHEMICALS FROM NORWEGIAN PETROLEUM ACTIVITIES (NPD)

2.4 RULES AND REGULATIONS FOR DISCHARGE OF OFFSHORE WASTE

In 1997 the Norwegian government issued a white paper named «Miljøvernpolitikk for en bærekraftig utvikling[1]», declaring a zero-discharge policy for oil and other chemicals that

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[1] Translation: environmental politics for sustainable development (my translation)

threaten the environment. This goal was a prerequisite for new-builds and was to be reached in 2005 for existing systems (Miljødepartementet 1997). According to the Norwegian law of pollution the operators of oilrigs on the Norwegian continental shelf have to report emissions to air and water, this includes emissions of slop water (Miljødirektoratet, 2013b).

Klif concluded in 2010 that the goal of zero-discharge was reached for harmful chemicals, but the goal for reduction of discharged oil and produced water was not. The predictions for the future of oil production is that the volume of produced and slop water will increase in the years to come. It is therefore with special interest that Klif will observe the discharges more closely and work to reduce the emissions further by even stricter regulations (Miljødirektoratet, 2013a).

Emissions and discharges from the Norwegian petroleum activities are regulated through several acts, including the Petroleum Act, the CO2 Tax Act, the Sales Tax Act, the Greenhouse Gas Emission Trading Act and the Pollution Control Act. The onshore petroleum facilities face the same policy instruments as other land-based industry. The general principles for handling waste from offshore activities in Norway are given by NORSOK environmental standard S-003. For more vulnerable areas, such as the south east part of the Barents Sea, more stringent regulations apply, incorporating the ISO 14001 standard. The oil content in discharges to sea is not to exceed 30mg/l, and according to the emission reports from the industry, the emissions are well below this limit.

Drilling waste composes near all the hazardous waste from offshore activities (Norsk Olje og Gass, 2013). The amount of waste sent to shore is ever increasing and dramatically so since the shut-down of several injection wells in 2010 and 2011. This leads to the assumption that rig operators send slop to shore in order to meet zero-discharge. This transportation, in turn, causes indirect environmental impacts that might overdo the benefits of lower emissions to sea.

2.5 SLOP WATER SOURCES

Slop water comes from three sites on a drilling platform: deck drainage water, cleaning of oil tanks or other equipment and drilling or displacement fluids contamination. In other words, processes where water and oil come in contact. The largest contributor in producing slop is the deck drains. Slop from displacement, drilling fluid contaminating and cleaning processes have the highest level of pollution. Parameters common to describe level of pollution in slop are oil and solids content. Heavily polluted slop contains over 35% oil and 10% solids, and could be classified as being slop mud (Mueller et al., 2013).

TABLE 2.2: ESTIMATES OF CONTRIBUTION FROM SLOP SOURCES AND LEVEL OF POLLUTION (OKIEMUTE, 2013)

Slop source	Level of pollution	Oil content [ppm]	Solids content [%v/v]	Estimated contribution of total slop
Deck drains	Light	<1000	<1	40-60%
Contaminated drilling/displacement fluid	Medium	<3500	<10	30-40%
Cleaning water	Medium	<3500	<10	10-20%

2.5.1 DECK DRAINAGE

On an offshore rig, there are both open and closed drain systems, which collect water from both hazardous and non-hazardous areas. The wastewater from non-hazardous areas such as the living quarters are generally discharged to the ocean without any treatment (DNV et al., 2012). This is not the case for the drain water from hazardous areas, such as for example the rig floor and the mud pit area, as they are likely to be contaminated with oil, drilling mud and other chemicals found on the drilling deck. This slop water is collected in tanks and treated as hazardous waste, according to NORSOK S-300. Good practices in keeping the two areas separate through barriers, not keeping chemicals stored in the non-hazardous area and preventing cross contamination is vital (Norsk Olje og Gass, 2012).

2.5.2 DECK, BOAT AND BARREL CLEANING

Cleanout of tanks on the rig and on supply boats generate slop water contaminated with de-emulsifiers, oil and detergent surfactants. This slop is usually reused a couple of times before routed to a slop holding tank. The de-emulsifier in the slop water makes the oil emulsify more easily into the water and is consequentially harder to remove from the water again in the treatment (Eia et al., 2006). The volume of slop produced from this part of the operation varies according to cleaning method, which can be manual or automatic, and the recycling rate.

2.5.3 DRILLING MUD AND DISPLACEMENT FLUID CONTAMINATION

When the drilling mud or the displacement fluid is no longer reusable because of water contamination, it becomes slop. Drilling mud is pumped down the borehole to remove cuttings from the wellbore and move it to the surface, cool and lubricate the drill bit, increase pressure in the wellbore to prevent the well from caving in and maintaining stability in the wellbore. There are three main types of drilling fluid, divided by the fluid base; water-based mud (WBM), oil-based mud (OBM) and synthetic-based mud (SBM). Water based drilling mud can be discharged without any treatment because it is considered to have low to none environmental effect. The fluid base for WBM can be fresh water, seawater or brine. The OBM on the other hand has a fluid base consisting of diesel or mineral oil. The use of OBM has risen because of its ability to give better lubrication and therefore the ability to drill faster, thus resulting in fewer rig days. In an attempt to reduce the toxicity of the OBMs but still maintaining its drilling qualities, SBM was developed. The fluid base in SBM can be diesel oil with reduced PAH content, synthetic paraffin or other oil like bases. For more specifics about drilling mud content see Appendix 9.1.

During well completion fluid displacement and wellbore clean up take place. Displacement also occurs during the cementing of the casings and when changing the type of drilling fluid. These processes remove mud and slurry from the wellbore to allow free passage through the drilled hole, thus enabling oil and gas production. This is achieved through mechanical scrapers combined with chemical pills or spacers, followed by seawater. These chemical pills can include different organic polymers, barite, viscosifiers and water. The resulting waste from this operation is slop water containing drilling mud, displacement fluids and solids.

3 TREATMENT SCENARIOS

After the slop is collected in tanks on the platform, it can either be injected, treated offshore or shipped onshore to a treatment facility. Direct discharge is not an option if the slop exceeds regulation discharge oil content limits. The details of the different treatment scenarios are presented in this chapter. The flowchart in figure 3.1 shows where the slop comes from, the different scenarios and how they are connected. The majority of slop water produced on NCS today is shipped and treated onshore. Injection has been a popular method of treatment until 2010-2011. The injection wells started leaking causing this practise to cease. Two parameters that distinguishes the injection scenario is that no transport logistics are required in the operation stage and it does not provide oil recovery. Offshore treatment is the newest contender in the marked and is rapidly gaining momentum because it decreases transportation costs.

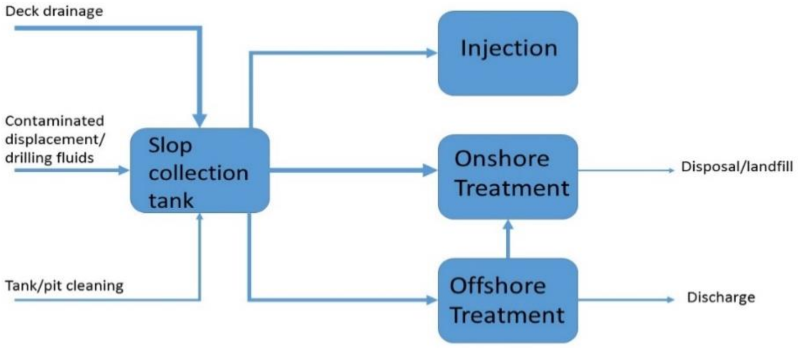


FIGURE 3.1: SLOP TREATMENT SCENARIOS AND SCOPE OF THESIS. THICKNESS OF FLOW ARROWS INDICATE VOLUME STREAM.

3.1 INJECTION

Deep well injection is a liquid waste disposal technology. This treatment alternative uses injection wells to place liquid waste into geologic formations that do not allow contaminants to escape. A typical injection well consists of concentric pipes, just like a production well, which extend thousands of feet down from the surface level into permeable injection zones that are sealed off by impassable rock layers. This is not always a possibility because of geological formations (Schuh et al., 1993). Either new injection wells can be drilled or old production wells can be repurposed to dispose drilling waste. Usually the waste from the first injection well will be discharged to sea without treatment, because there is no other injection well available, and it is deemed viable (James and Rørvik, 2002).

This method of disposal was very popular until in 2010-2011when it was discovered that many of these injection wells on the NCS were leaking the waste to sea. Nearly all injection activity stalled in this period, but new and better technologies have emerged and in 2013 a whopping 28 injection wells were drilled on the NCS (Oljedirektoratet, 2014). This is a sign of renewed faith and maybe injection will be the most popular route to go.

Slop is often mixed with crushed cuttings and viscosifiers to make slurry. This slurryfication process prepares the waste for injection into well and increases its volume drastically (Dahl-Hansen et al., 2012, Svensen et al., 2011, DNV and Karlsen, 2012). Slop is also injected without any prior treatment or mixing with other wastes.

This method of waste treatment is close to the source and transportation is unnecessary, making it the most environmentally friendly option during operation. In 2010 and in 2011 several injection wells on the NCS were found to be leaking and could not be used any longer, resulting in an increase in slop and cuttings transported to shore (DNV and Karlsen, 2012).

3.1.1 INJECTION PUMP

Various pumps are used throughout all the scenarios, dosing pumps, feed pumps and larger pumps for injection into well. For this last purpose the use of a "High pressure pump, HT400" is common (James and Rørvik, 2002, Norsk Olje og Gass, 2012). This pump is delivered by Halliburton and is an old and trusted pump technology. The HT stand for Horizontal Triplex referring to the design and alignment of the pump.

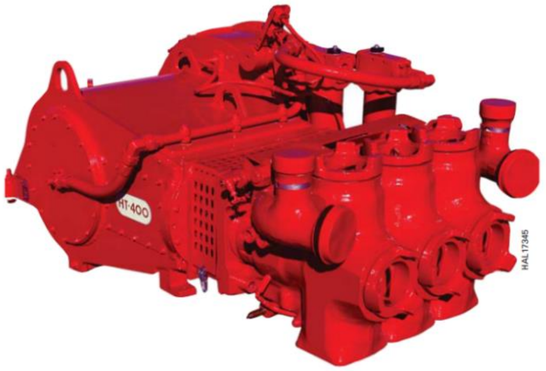


FIGURE 3.2: HT 400 HIGH INJECTION PUMP (HALLIBURTON)

3.2 ONSHORE TREATMENT

There are a number of different technologies used for wastewater treatment. The aim for most of them is to separate the oil and particles from the water, others are geared towards specific chemicals, pH and salt content. The most common processes for treating oily wastewater are sedimentation, centrifugal separation, coagulation and flocculation, sorption, flotation, ultra filtration and reverse osmosis (Pushkarev et al., 1983). Rapports from DNV show that the capacity for treatment of the anticipated increasing amount of slop water is well covered in Norway (DNV and Karlsen, 2012)

The first thing the wastewater undergoes is some form of rough separation aiming at reducing the oil and grease content to a more acceptable level for the other treatment technologies downstream. Sedimentation, hydrocyclones or dissolved air flotation are typical processes in achieving this. The second stage can be a physical or biological treatment, or both. This stage will continue the work of the first stage and further reduce the oil and grease content. At stage three the treatment technologies are much more refined and need water of high quality to function properly, hence the two preliminary stages. Here we can find activated carbon, membranes or organoclay technologies for filtration of the ultrafine oil and grease particles. A fourth stage can be part of the process to remove dissolved pollutants like sodium, totally dissolved solids and boron (Vlasopoulos et al., 2006).

The sludge resulting from these separation processes needs further treatment. This can include additional separation of the sludge in a centrifuge of some kind and finally a TCC process. The output of these final processes can be disposed of or sold to a third party.

3.2.1 SKIP AND SHIP CHAIN

Transportation to shore requires the use of cranes to lift skips onto a vessel of transportation. A generic well will need approximately 152 skips and 765 crane lifts which is a serious health and safety issue. Statoil wants to minimize the use of crane lifting due to the hazard of falling objects and pinch points. There are issues related to the capacity of the skip and ship chain. Drilling a 17,5 inch well at average ROP of 45 m/hr typically generates 9 m^3/hr of cuttings. This leads to 15 crane lifts per hour, which leads to the conclusion that it is unlikely that the crew on the platform will be able to keep up with the amount of waste being produced, thus lowering the ROP if there is not sufficient storage alternatives are available. In times of long lead times due to capacity onshore, the waste froze during the winters of 2009 and 2010. (Svensen and Taugbol, 2011). This information argues that the transport of drilling waste can be precarious, ineffective and slow down drilling processes.

3.2.2 COAGULATION AND FLOCCULATION

Coagulation and flocculation are separation by chemical reactions and consists of two successive steps. First coagulants are added to the wastewater and need to be thoroughly mixed. The purpose of the coagulant is to destabilise the particles or oil droplets charge so they do not repel each other anymore, but can come together to form microflocs not visible to the naked eye. Typical coagulants are ironcloride (FeCl3), aluminium sulphate (Al2(SO4)3), lime (CaO), clay and powdered diatomite (Puszkarewicz, 2008). The coagulant needs to have charges opposite of the oil and particles to work.

Following the coagulation is the flocculation process, which is a gentle mixing stage. This mixing will make the microflocs stick together to form larger pinflocs and macroflocs through collisions between the flocs and interaction with polymers promoting aggregation and coalescence. To avoid re-emulsifying of the oil the mixing must be kept at a low speed. Once the flocs have reached the desired size and strength they are ready to be deposited in sedimentation tanks or they can be separated by dissolved air flotation. Flocculated solids are sometimes treated with a filter to decrease the water content and thereby the volume to produce a dry filter cake.

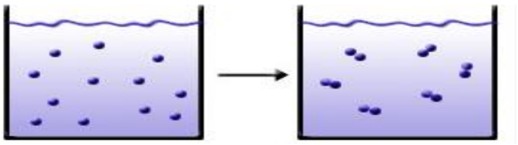


FIGURE 3.3: ILLUSTRATION OF THE FLOCCULATION PROCESS:

3.2.3 DISSOLVED AIR FLOTATION

Separation of slop water is enhanced by the method of dissolved air flotation or DAF. Air is dissolved into water under pressure and injected into the wastewater. When released the dissolved air pressure drops and air bubbles form and attach themselves to oil droplets or particles. This gives a higher buoyancy and the droplets and particles rise to the surface of the wastewater where they can be removed. The efficiency of separation is dependant of oil droplet size, oil and gas concentration, and type of oil. Oil removal efficiency by dissolved air flotation can be as high as 60% at low flow rates (Mueller et al., 2013). Flotation is usually done after a flocculation stage to further increase the rate of oil and particle removal.

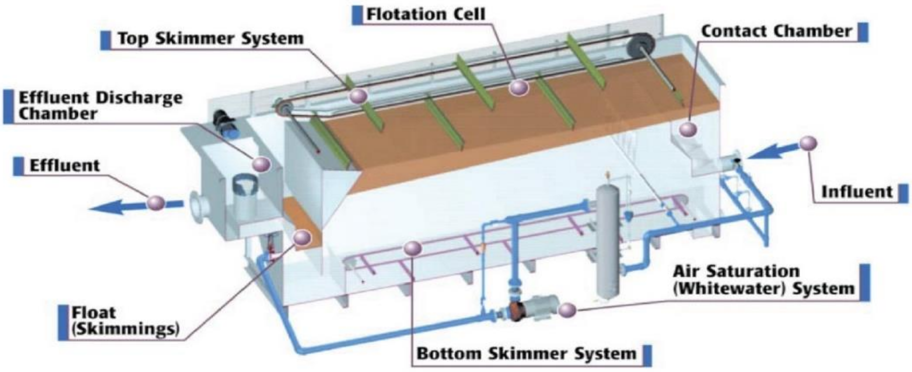


FIGURE 3.4: DAF UNIT, SHOWING THE FLOCS IN BROWN AT THE TOP OF THE COMPARTMENT, TOP SKIMMING, BOTTOM SKIMMER TO TAKE AWAY SETTLED SOLIDS (ENVIRONMENTALTREATMENTSYSTEMS ET AL., 2003)

3.2.4 SEPARATION

Separation of the different phases in the slop water can be done mechanically or chemically. One method of separation is using centrifugal force and taking advantage of the different densities in the different phases in the waste, causing the denser substances to separate along the radial direction. This effect is used in decanting centrifuges, disc stack centrifuges and hydrocyclones, which all use the same principle but execute it in different ways. Decanters that phase out three different product, also called tricanters, can be useful when dealing with slop water whom contains three different phases; oil, water and solids.

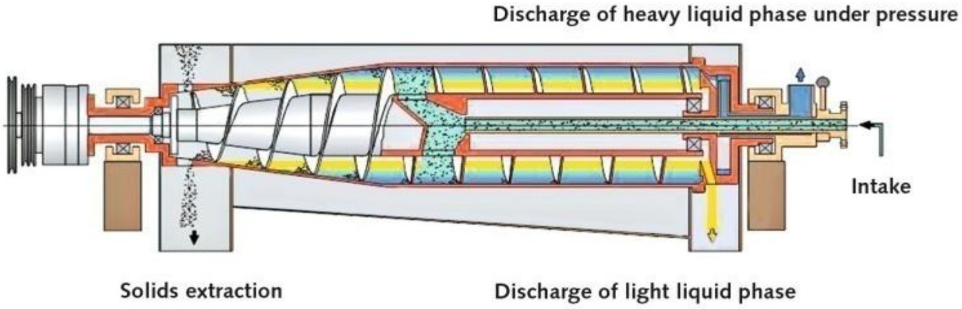


FIGURE 3.5: THREE PHASE DECANTER, TRICANTER (FLOTTWEG)

3.2.5 BIOLOGICAL TREATMENT

Biological treatment uses micro-organisms to remove organic compounds from the wastewater. This process requires specific temperatures, oxygen levels and nutrients for the micro-organisms to thrive. The bacteria eat the oil to produce new cells, by-products are carbon dioxide and water. This process is described by the following equation:

$$\text{Organic material} + O_2 + \text{nutrients} \longrightarrow CO_2 + H_2O + \text{new cells} + \text{nutrients} + \text{energy}$$

Biodegradation reduces the oil content, the chemical oxygen demand (COD), a measure of organic compounds in the water and total organic carbon (TOC). These values are all a part of the discharge criteria for onshore facilities. Biological treatment is space and time-consuming and is therefore not used on offshore installations, where space is limited. This treatment is very sensible to changes in the climate and to the level of oxygen or nutrients and need proper surveillance to keep the process at an optimal level. The micro-organisms can be introduced to the wastewater through a fixed substrate, which is called attached growth, or constantly mixed with the wastewater, called suspended growth system (Lofrano et al., 2010).

3.2.6 THERMOMECHANICAL CUTTINGS CLEANER

Thermomechanical Cuttings Cleaner is a form of thermal evaporation treatment where kinetic energy is used to heat the waste. At a specific temperature the oil and the water will evaporate, leaving the oil free solid particles behind. The kinetic energy is caused by creating friction in the waste itself by driving a series of shaft-mounted hammers into motion inside a process mill. This forces the solid particles in the waste towards the inner wall of the mill where the kinetic energy of the hammers will turn into heat through friction. This way of heating the waste to make the water and oil evaporate is unique. Other technologies use indirect heat, risking fires and they require much more space. This is why the TCC technology is often used in offshore treatment of waste water, where there is limited space and many combustibles aboard (Termtech) (Bazilchuk et al., 2006).

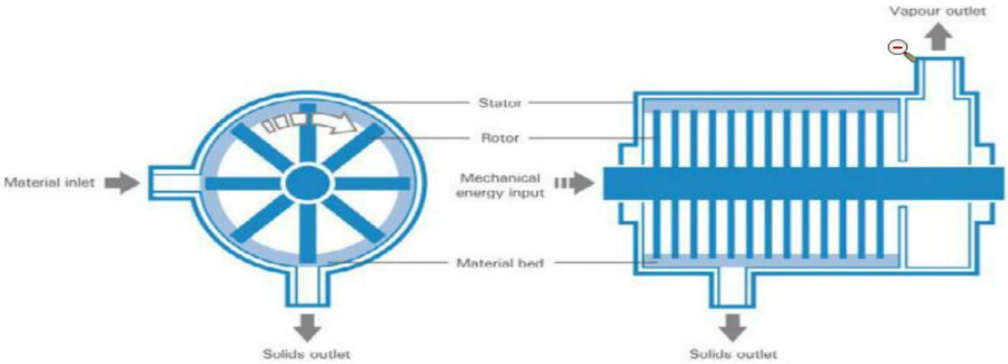


FIGURE 3.6: SCHEMATIC DRAWING OF A TCC-UNIT (TERMTECH)

The TCC delivers recovered oil of high quality. The oil is not degraded through the refining process and can be used again in drilling mud or for other purposes. The performance of the TCC is highly dependent of the water content of the sludge it is fed. The higher percentage of water, the more energy is needed to elevate the temperature to the required level. The slop water should therefore undergo separation before it reaches this process, only dense sludge should go through the TCC.

3.3 OFFSHORE TREATMENT

With the recent developments of injection wells failing and the economic burden of transporting slop to land for proper treatment, the alternative of offshore treatment is becoming more popular. On offshore installations, there are always limitations on available space for both treating and holding the slop water. That is why the treatment units are relatively small compared to the onshore equivalent, and they do not treat the full chain of slop water waste. Toxic sludge from initial treatment offshore needs transportation onshore for the final treatment and disposal.

There are many different procedures and techniques used on different rigs, but the technologies used will mimic the ones onshore. According to the emission reports from Norwegian oil and Gas only 40% of the slop producing rigs have a slop treatment unit installed, the rest inject it or send it onshore. This percentage reduces if taking into account each rigs level of activity and the amount of slop each rig produces. The components of a rig are also interchangeable and one rig can have used several treatment alternatives during a year. The largest suppliers of slop treatment on the NCS are Halliburton, M-I Swaco and Baker Hughes. The two most used techniques for treating slop are a flotation treatment and a mechanical treatment process, and these are therefore the basis for the offshore model. Some other technologies, like the use of micro filters and membranes exits to a small degree (Norsk Olje og Gass, 2012). On English platforms, it has become more common to install a TCC unit to handle cuttings and contaminated solid. Slop requires prior treatment if to be processed by a TCC, because of the high water content.

Offshore slop treatment using flotation include processes of flocculation and flotation. The descriptions of these processes are found in chapters 3.2.2 and 3.2.3. The mechanical slop treatment process comprises of a decanter, centrifuge separation and filtration, described in chapters 3.2.4 and 3.3.1.

3.3.1 FILTRATION

Filtration using activated carbon or charcoal filters are common and they absorb organic non-polar substances like mineral oil, benzene tolulene and poly aromatic hydrocarbons. Membrane technology is another form of filtration where the water is pumped through a hydrophilic membrane to repel the oil and let the water through. The membrane has a positive pore structure catching oil and solids producing a concentrated waste and clearer water. A cruder, upstream filtration that can occur earlier in a treatment process is bag filters. They remove solids from the bottom of oil-water separators (Al-Ani, 2012). Filters are used everywhere where wastewater is treated, either it is slop water, municipal wastewater or other liquid wastes.

4 METHODOLOGY

This chapter descries the Life Cycle Assessment method and its framework. Then follows an explanation of LCA terms and some of the criticism of the method. Lastly the simulation tools, database and impact assessment tool are described.

4.1 METHOD

This study is about a LCA model concerning a waste product; slop water. Early development of LCA in the 1970»s was largely driven by packaging and packaging waste. Also, later in the history of LCA, waste managing has played a large part in further developing of the method, but the more traditional approach is to focus not so much on the waste, but rather on the whole lifespan of a product. LCA was first applied in the field of wastewater in the 1990»s, this made it clear that LCA is a valuable tool to assess the environmental effects of the design and operation of the wastewater treatment systems (Corominasa et al., 2013).

The aim of a Life Cycle Assessment analysis is to inspect the whole lifespan of a product, process or service from production to disposal, from cradle to grave, and then evaluate the environmental impact it has. That typically includes extracting raw materials, manufacturing, distribution, use, reuse or maintenance, recycling and disposal, and all the transport needed in between these processing phases (SETAC et al., 1993, Lindfors et al., 1995). The different phases of the product's lifespan are usually divided into production, use and disposal. This extended perspective of environmental analysis is important because the indirect environmental impacts of the surrounding processes can often outdo the direct impacts (Ekvall et al., 2007b).

The LCA method is a tool to optimize production, develop and compare products and to highlight areas to reduce emissions. LCA addresses environmental impacts in ecological systems, human health and resource depletion, but it does not include economic and social effects (Lindfors et al., 1995).

The framework of a LCA is given by the ILCD Handbook and the leading standards ISO 14044 «Environmental management - Life cycle assessment - Principles and framework» and ISO 14040 «Environmental management - Life cycle assessment - Requirements and guidelines», both issued in 2006. There are several, distinct steps to an LCA study, according to the ISO standard 14044/14040 they are:

1. Definition of scope and goal
2. Life cycle inventory analysis
3. Environmental impact assessment
4. Interpretation

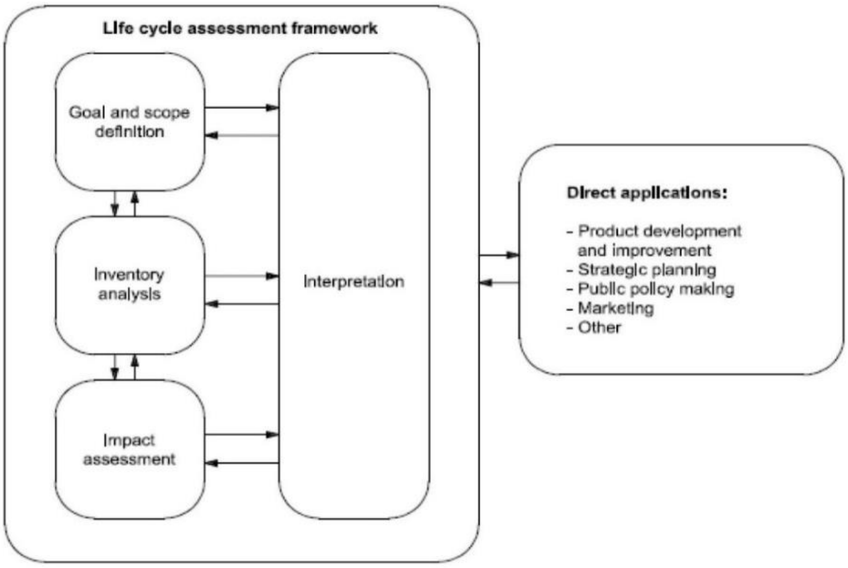


FIGURE 4.1: LCA FRAMEWORK (ISO14040, 2006)

The first step of an LCA study is to find a product or process to analyse and then define the goal of the study. This initial phase of the study is where the functional unit and the system boundaries are decided, but this decision is often revisited several times during the study. Next follows the inventory analysis based on a flowchart of the different aspects and processes when making the product. Inventory analysis is to gather of information about what substances and energy goes into a process, and what comes out of it. This data is analysed in a life cycle impact assessment. This is where the large amounts of resulting data are aggregated and weighted to get values that are easier to understand in terms of environmental impact. For instance from amount of a greenhouse gas emitted, converted to CO_2 equivalents to a weighted contribution in the global warming potential category. Interpretation of the results of the analysis is the final part of the study where the most important features are highlighted. This shows where the largest contributing processes are and what needs improving. A sensitivity analysis is conducted to test the uncertainties in the data and basic assumptions and how they affect the impact results.

It is important to recognize that an LCA is a simplified version of the real system and the environmental impacts and therefore cannot give an accurate representation of what happens. When analysing the results of a LCA it is common and necessary to evaluate the validity of your values and results, their variance and the model itself. The quality checking should be repeated all through the LCA study, as an iterative process to make sure that the qualitative data meets the quality requirements defined in the goal and scope of the project. (Lindfors et al., 1995).

4.1.1 LCA OF WASTE PROCESSES

There are many different ways of handling waste, from recycling and reuse to energy recovery and landfill depositing. This is even an integral part of LCAs that are more product-focused. The focus of a waste management LCA is to find the best treatment option, and from an environmental point of view (Baumann, 2004). As mentioned previously, the waste management system itself may not be responsible for the greatest environmental impacts, but rather the surrounding systems. LCA is a good tool to analyse such a system because it not only includes emissions and impacts occurring throughout the whole lifespan, but also significant environmental benefits of waste management alternatives such as recycling replacing production, energy recovery through incineration and using the waste in an entirely different setting (Ekvall et al., 2007b).

The functional unit in a waste management LCA differs from a product LCA. Where the product LCA has a functional unit that is usually a given amount of output, say a tonne of steel, in waste management LCA the functional unit is the input to the system, such as 1000 m^3 of waste water. This view is more helpful in a waste LCA because there can be many different outputs from a treatment facility, and different technologies and setups give different outputs as well. These multiple and varying outputs make it difficult to compare and evaluate different treatment technologies. The functional unit is fixed to ensure comparability.

4.1.2 LIMITATIONS TO THE LCA METHOD.

Critics of the LCA method usually note the lack of flexibility in the method and the subjective affect the LCA practitioner has on the study. The biggest challenge for any LCA study is to collect the right numeric data from reliable sources. Average, outdated and inaccurate data can compromise the results of the study and therefore a high level of transparency documenting the sources of the data and verifying using multiple, independent sources is important for any study. Another critique of LCA is that it does not include aspects that cannot be quantified such as socio economic benefits (UNEP, 2009).

4.1.3 CUT-OFF, ALLOCATION, ZERO BURDEN ASSUMPTION

Cut-off is a tool to make the system more comprehensible by omitting non-relevant life cycle stages, processes and elementary flows in the system. Cut-off rules are quantified in relation to the percentage of total environmental impacts. This choice and its effect on the outcome of the study must be clearly described in the inclusions of inputs and outputs and the assumptions (European Comission, 2010).

Another tool used in LCA is allocation. This is used when you have several different outputs from one process. Allocation decides how much of the emissions in this process to attribute to each of the outputs. This division can be based upon mass fractions or even monetary or value fractions. There is another way of dealing with allocation issues, preferred by the ISO standard, which is system expansion. This tool avoids the whole need for allocation by expanding the system and including more processes.

Traditionally the waste in an LCA of Waste Management Systems is treated as it has no burdens associated with it. This is to evaluate the process in focus for the LCA and not necessarily the production of the waste. In other words the waste does not carry with it all the upstream emissions, they are omitted as a simplification of the system. This approach is also called Gate-to-grave and has some drawbacks; since the waste is considered “free” there are no incentives to optimally utilize the input waste (Ekvall et al., 2007a).

4.2 MODELLING TOOLS AND ASSUMPTIONS

The tool used when conducting and calculating the LCA in this study is SimaPro, a commercial software used in the business. Quantitative and qualitative input and output data are put into the corresponding process. The processes are linked to one another to make the entire system. SimaPro utilises databases, and in this project the Ecoinvent 3.0 database was used. This database has an extensive collection of processes and is updated continuously. In this new version of Ecoinvent there is a distinction between attributional and consequential LCA. Attributional life cycle assessment focuses on describing the environmentally relevant physical flows to and from a product or process, while consequential assessment describes how relevant environmental flows will change in response to possible decisions (Finnveden et al., 2009). This paper compares several attributional LCAs. In addition to the Ecoinvent library of processes, some relevant processes found in the MiSA library have been utilized. These processes have been constructed by the company and are not a part of any standard LCA database.

4.2.1 LIFE CYCLE IMPACT ASSESSMENT CATEGORIES

The life cycle impact assessment portion of an LCA consists of an evaluation of both human end environmental impact of the resource use and emissions quantified in the life cycle inventory (SAIC, 2006). An impact category is defined as “a class representing environmental issues of concern into which LCI results may be assigned” (Bruijn et al., 2002). The different impact categories and their properties are listed in table 4.1, to clarify the correlation between LCI data and environmental impact, before we proceed to the results.

TABLE 4.1: IMPACT CATEGORIES AND THEIR PROPERTIES

Impact category	Unit	Scale	Char. Factor	Description
Climate change	kg (CO2 to air)	Global	CC	Converts LCI data on GHGs like CO2, NO2,CH4, CFCs, HCFCs,CH3Br to carbon dioxide (CO2) equivalents
Resource depletion	kg of resource, metal of fossil	Global, Regional, Local	RDP	Converts LCI data on water, metals and fossil fuels used to a ratio of quantity of resource used versus quantity of resource left in reserve.
Ecotoxicity, Terrestrial and Aquatic	kg (14DCB to soil or water)	Global, Regional, Local	ETP	Converts LC50 data on toxins to equivalents using multimedia exposure pathways.
Eutrophication, Freshwater and Marine	kg (N or P to water)	Local	FEP/ MEP	Converts LCI data on PO4, NO, NO2, Nitrates and NH4 to phosphate (PO4) equivalents
Acidification, Terrestrial and Aquatic	kg (SO2 to air or water)	Local, Regional	TAP/ AAP	Converts LCI data on acids like SOx, NOx, HCL, HF, NH4 to hydrogen (H+) ion equivalents.
Human toxicity	kg (14DCB to urban air)	Global, Regional, Local	HTP	Converts LC50 data on toxins to equivalents using multimedia exposure pathways.
Ionising Radiation	kg (U235 to air)	Local	IRP	Converts LCI data on radioactive substances to U235 equivalents.
Ozone depletion	kg(CFC115 to air)	Global	ODP	Converts LCI data on halons, CH3Br, chloroflorcarbons and hydrochlorofluorcarbons to trichlorofluoromethane (CFC-115) equivalents
Particulate matter formation	kg (PM10 to air)	Global, Regional, Local	PMFP	Converts LCI data on TOC, heavy metals, smoke, dust and spores to PM10 equivalents.
Photochemical oxidant formation	kg (NMVOC6 to air)	Local, Regional	POFP	Converts LCI data on substances like benzene, ethanol, cyclohexane and acetone to NMVOC6 equivalents.
Land use	m^2 * yr	Global, Regional, Local	LOP	Converts mass of solid waste into volume using an estimated density

The ISO standard requires a selection of impact categories that reflect the issues of the studied system. Therefore, not all of the 18 midpoint impact categories were considered in the life cycle impact assessment. Only the most important ones for this project have been considered. The impact categories shown in the results are the eight most important categories for this study; climate change, ozone depletion, freshwater eutrophication, human toxicity, particulate matter formation, natural land transformation, marine ecotoxicity and fossil depletion.

4.2.2 ReCiPe

ReCiPe is the framework used to calculate the life cycle impact assessment, which has three different perspectives; individualist, hierarchical and egalitarian. These perspectives were introduced by Hofstetter in 1998 and are based on cultural theory in social sciences (Ciroth et al., 2011). The differentiating factor between these is the timeframe ranging from 20 years to eternity.

- The Individual perspective is the short term one, with the optimistic philosophy that technological advances can avoid many problems in the future.
- The Hierarchical perspective has a medium timeframe and is generally used in scientific models and is the one with the largest consensus.
- The Egalitarian perspective has the longest timeframe and is a precautionary perspective. It is therefore the more pessimistic one focusing on the long term. In this thesis the hierarchic perspective (H) is chosen because it is the middle way of the three perspectives, it is neither optimistic nor pessimistic in its approach. The impacts at midpoint level are aggregated into three endpoint impacts (Goedkoop et al., 2009).

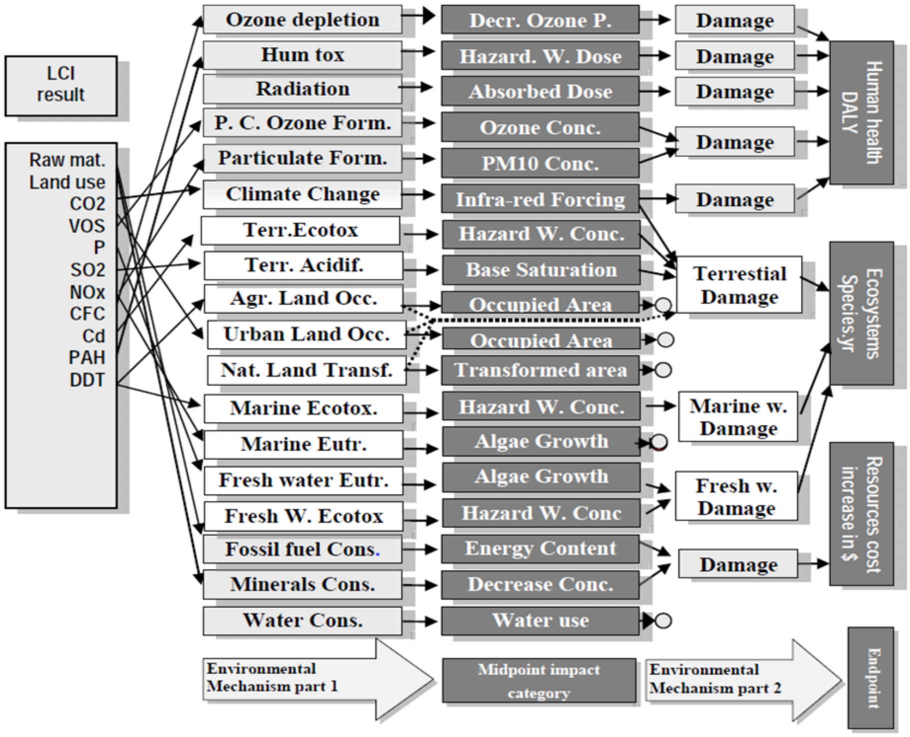


Figure 4.2: ReCiPe framework (Goedkoop M.J. 2009)

The ReCiPe methodology is based on the CML 2000 and the EcoIndicator 99 methodology. The CML 2000 focuses on midpoint indicators, whereas the EcoIndicator 99 has a focus on endpoint indicators. The ReCiPe methodology was created with the underlying thought of uniting the two. The midpoint indicators have a relatively low uncertainty and high acceptance within the LCA community. The endpoint indicators have in comparison relatively high uncertainty (Goedkoop et al., 2009)

5 LIFE CYCLE INVENTORY ASSESSMENT

In this chapter the systems within each of the three scenarios explained in chapter 3, is defined together with the system boundaries. Initially a description of the sources for the inventory and how they are used is presented along with general assumptions made when building the model. Subsequently each scenario is presented separately with flow diagrams of the system.

5.1 SYSTEM DESCRIPTIONS

In this study, three different ways of treating slop water are investigated and compared. In the case of offshore treatment, there are interactions with the onshore scenario. The models are based on a process flowchart retrieved from the available data. The model gives directions to how the process is transformed into an inventory system, stating how a functional unit influences the environment by using technological relations in the model (Berg et al., 1999). Figure 5.1 shows the three different scenarios, the processes used to build them and the colour coding shows where the information to set up the inventory came from.

Yellow indicates inventories made in my project thesis and revolves around the treatment facility in Mongstad owned by Halliburton. The inventory has been reviewed for this work and alterations to transport and water use have been made. Parts of this inventory are reused in the offshore scenario for the final treatment of the sludge.

The offshore treatment inventory, green coding, is inspired by work done by Anthony Okiemute for his project thesis. Information found in the NOGA emission rapports and manufacturers of offshore treatment units, resulted in two alternative offshore treatment technologies, one mechanical separation and one flotation separation. Some parts of Anthony's inventory fit in these technologies with some revision and additions.

The red areas are inventory data based on Arild Saasen's article from 2014, comparing energy used in injecting drilling waste and shipping it to onshore treatment. To make a complete inventory over the processes highlighted, it has been expanded from only energy to include drilling fluids, casings for well and energy required to pump slop down the well. These well production processes are taken from the MiSA process library, marked in grey.

The blue areas are inventories that are not based on any other inventory, but built up from scratch by myself, with help from other sources. The blue line around the whole model indicates that the building of the system is done by me.

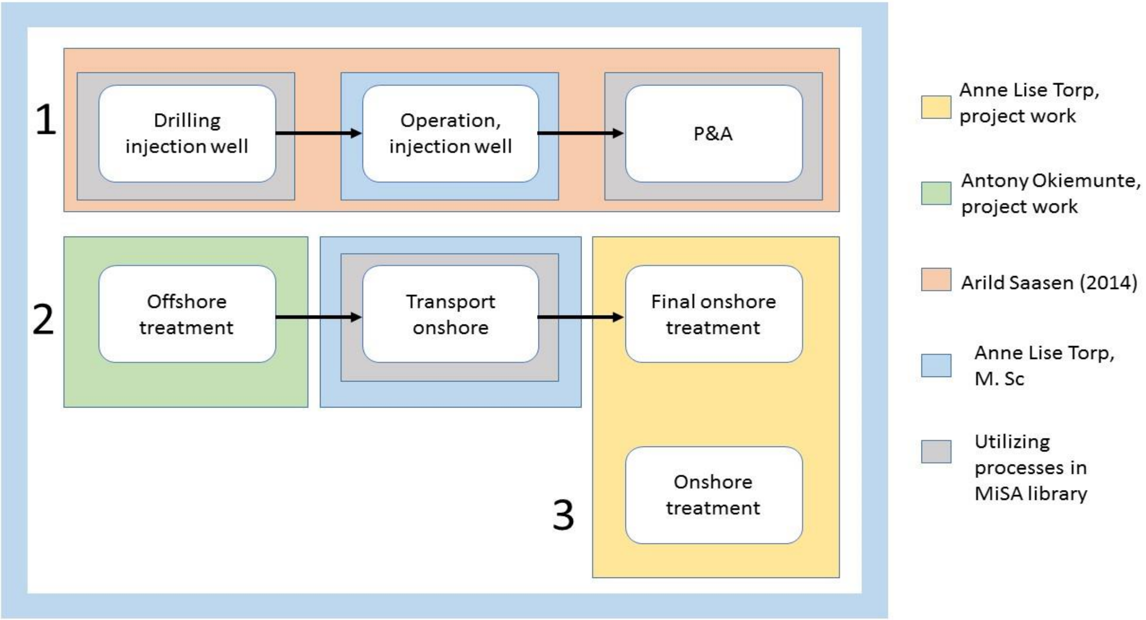


FIGURE 5.1: INVENTORY SOURCES

5.1.1 GENERAL ASSUMPTIONS MADE WHEN BUILDING THE MODEL:

Functional unit in the model is the treatment of 1 m^3 of slop water. That means incoming slop to the system, which is characteristic for waste treatment LCAs. The system boundaries encapsulate the operation of all the different treatment scenarios and the disposal of the waste, although in the injection scenario the operation is the disposal. The production of the waste itself is not included in the model, and is zero burden. Other elements not included in the model are the raw materials needed for equipment and construction of the different machinery used in the different processes. The lifetime of this machinery is assumed very long, hence the impact that they pose is presumably negligible.

The construction of an injection well is included in the injection scenario, based on Saasen’s comparisons of energy used in injection and shipping to onshore treatment. It showed that the drilling of an injection well is the most energy intensive part of an injection scenario and should not be overlooked. Transportation in different forms is a crucial part of the model, a parameter of discussion in the juxtaposition of the scenarios and pose a financial and health threat.

One important simplification of the model is that it only includes treatment of slop water. In the injection and the onshore treatment scenario, other types of offshore drilling waste can be included in the treatment, such as cuttings and produced water. This will implement the allocation of impacts between several outputs and is outside the scope of the thesis, but possibly closer to the real operation of an injection pump. In addition, it is assumed that the injection is solemnly for disposal purposes and not for enhanced oil recovery, which would include more processing.

A set of estimated and calculated densities used throughout the inventory are shown in table 5.1. These densities were used in the process of mass balancing the flows in the models and to alter units.

TABLE 5.1: DENSITIES OF SUBSTANCES USED IN THE MODEL

Product	Density		Comment
Slop water	1010	kg/m^3	Calculated by adding up the percentagewise concentrations of the components, given by (UiS and Halliburton, 2013): 80% water (1000 kg/m^3) 10% oil (900 kg/m^3) 10% solids (1200 kg/m^3).
Drilling sludge/fluid, oil based	2200	kg/m^3	Provided by Halliburton
Solids	1200	kg/m^3	Average of types of solids found in the slop water
Oil	900	kg/m^3	Average of oil types found in Engineering Handbook (Engineering Toolbox)

5.2 INJECTION SCENARIO

Injection of slop water down under a formation, below the seabed involves the least amount of processing, compared to the other treatment scenarios. No chemicals are added during operation and there are no separation processes included. It does require an injection well to be drilled and closed when injection is completed, and a pump to transport the slop from the rig and down below the seabed.

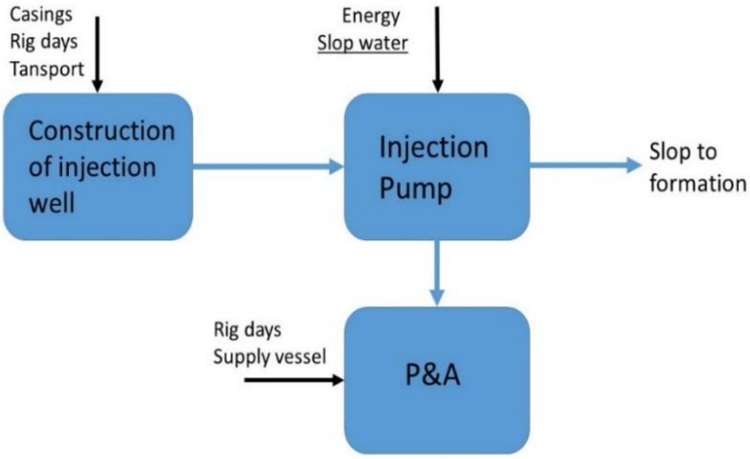


FIGURE 5.2: SCHEMATIC OVER THE PROCESSES INVOLVED IN THE LIFE-TIME OF INJECTING OF SLOP WATER

5.2.1 CONSTRUCTION OF INJECTION WELL

The basis for the inventory of a drilling process is an injection well on the NCS at Utsirahøgda. The specifics of this well are described in table 5.2 and portrays a well drilled solely with WBM. The formation surrounding the injection well is assumed to hold the waste of 13 wells on the field, a total of 43573 m^3 (Saasen et al., 2014). This range of injected volumes can also be found in a case study from Valhall oil field (Moschovidis et al., 1994).

The amount of waste a formation can hold will vary greatly, and depends on the size of the formation field and the permeability of the rock. The example well used here may probably have a larger capacity for disposal, depending on how it responds to the pressure build-up of the injection.

TABLE 5.2: PROPERTIES OF THE DISPOSAL WELL (SAASEN ET AL.):

Properties of well	
16" section of well	570 m
13,625" of well	412 m
Rig days needed for drilling	25 d
Rig days needed for P&A	10 d
WBM used	450 m^3
Expected to hold, volume of waste	43 573 m^3

DRILLING FLUID

The spud mud used for the initial, largest section of the well is assumed to be seawater and not included in the inventory because of its negligible environmental impacts. The choice of drilling mud is a crucial one. As mentioned before, drilling with OBM results in more slop water needing treatment. Choosing which WBM to use also influences the final environmental impact of the whole process. Saasen assumes a water based mud consisting of mainly KCl brine, barite and organic polymers (Saasen et al., 2014). These assumptions lead to a choice of two different WBM found in the MISA database: Gydril and Performadril. Both muds are frequently used in drilling on the NCS (Norsk Olje og Gass, 2012). For this inventory Gydril (MISAtest4055700076) is used and contains 50% water, 43% of KCl in a 20% dilution, barite for increased S.G and a selection of polymers. When selecting Performadril the environmental impacts from it completely overpower the rest of the system. There will be more about this in the sensitivity analysis.

DRILLING RIG

The well is expected to be drilled by a semisubmersible rig, because this type of drilling rig is a common one on the North Sea. This type of rig uses more energy than a jack-up rig that has legs all the way down to the seabed, because it needs to use turbines to keep in position. A semisub is more suited for deep water drilling, which is the case in the North Sea. The rig is assumed floating, not anchored, because of the short drilling time. These assumptions entails a doubling of the energy use, compared to when the rig is anchored. The selected process for this rig is «Drilling Rig, drilling operations, dynamic positioning» (process identifier: MISAtest40557000018). The input in this process is «Diesel burnt in diesel-electric generating set on rig». The inputs to this process again consists of the Ecoinvent processes for diesel, lubricating oil and production of electricity from a diesel generator. Drilling and completion of this well is expected to take 25 days. This amount of time is a relatively conservative estimate (Oljedirektoratet, 2014).

SUPPLY VESSEL AND HELICOPTER TRANSPORT

During drilling there will be a need for a standby vessel. Estimation of the number of roundtrips performed by the standby vessel is about 400 km, three times a week, resulting in 17 roundtrips in total which is equal to 6800km. The distance used is an estimated distance from Utsirahøgda to base location Kårstø, and back again (Statoil, 2012). The MISA process «Far serenade, at economy speed (11,3kn)» was used as the offshore supply vessel used for oilfield to onshore base transportation. This specific vessel was chosen because it has the middle value fuel consumption in the MISA supply vessel catalogue. In lack of specifications as to which supply vessels were used, the average will suffice. The input to this transportation process is just energy in the form of the process «Combustion of marine diesel oil, on offshore supply vessel at sea». This process includes diesel consumption and the emission to air correlating to its combustion. To calculate the operating time the travelling speed of 11.3 knots was converted to 21 km/h and divided by the distance, resulting in 323,8 hours.

Helicopter traffic is also included, and estimated to be four flights a week, making the total amount of helicopter transport to be 8000km. With an average cruising speed of 131 knots, this is equal to nearly 33 hours of flight time (Saasen et al., 2014, Bell Helicopters, 2014). The process used in the inventory for this is the Ecoinvent process «Transport, helicopter {GLO}| market for| Alloc def U», and incorporates consumption of kerosene, aluminium and enforced steel used in the construction of the helicopter and emission to air mainly GHGs.

FRACKING FLUID

During completion of the well hydroxyethyl cellulose, or guar gum, is pumped into the well for opening a fracture. This is a sea water polymer used as a viscosifier, it thickens the water (Saasen et al., 2014). Fracking fluid consists of almost 99% water with the last percent being additives. The concentration of hydroxyethyl cellulose is 2,4 to 6 kg per m3 of water (Weatherford). The amount of fracking fluid used is individual to each well, and the range is large. For horizontal fracking from 10 000 m3 to 20 000 m3 is used, and this method consumes more than conventional fracking. Staying on the conservative side, a volume of 10 000 m3 was chosen, which leads to 42 000kg of hydroxyethyl cellulose (AEA, 2012). This exact chemical was not found in the Ecoinvent database, so a substitution was made. The process used in the model is «Carboxymethyl cellulose, powder {GLO}|market for| Alloc Def, U», which is also a type of gum cellulose frequently used as a food additive for its viscosity properties just like hydroxyethyl cellulose (GSFA, 2013).

5.2.2 OPERATION OF SLOP INJECTION

Slop water needs no additional treatment prior to injection (Saasen 2014). If the slop is mixed with cuttings to make a slurry, before injection, both chemical and mechanical treatment is needed. This is an example of further studies, and it is outside the scope of this thesis. The only direct emissions associated with the injection of slop, are in the case of spillage or other malfunctions. Indirect emissions are linked to the use of energy for the injection pump.

INJECTION PUMP

On the Eldfisk Alpha 2/7A platform they use two HT-400 displacement pumps which pump slurry down the injection well at 6800vertical feet. The pumps require 320kW each to reach 3400psi needed for the reinjection (James and Rørvik, 2002, Norsk Olje og Gass, 2012). It is estimated that these pumps use 140,6 kWh/ton (James and Rørvik, 2002) which leads to 142 kWh/m^3 based on the densities in table 4.2. This is modelled using the Ecoinvent process «Diesel, burned in electric-diesel generating set {GLO}|market for|Alloc Def.U».

5.2.3 PLUG AND ABANDONMENT

At the end of the life cycle of an injection well it needs to be closed and sealed properly. This operation is called plug and abandonment (P&A) and requires 10 additional rig days. In the inventory the same rig as used for drilling the well is used. A cement plug caps off the well and should be at least 60 m long, in the smallest casing (OISD, 2013). A cement volume of 5,1 m^3 will suffice for this purpose, and equals 7680,6 kg assuming cement density of 1506kg/m^3. The process used in the inventory is «Cement, Portland {CH}|Alloc Def, U», found in the Ecoinvent database. Helicopter and supply vessel transport is modelled the same way as in the drilling process.

5.3 ONSHORE TREATMENT

The onshore treatment of slop water is based on an actual facility in Mongstad, operated by Halliburton. The inventory for this model was built in my project paper, from the autumn of 2013, with some modifications. Halliburton gave most of the information needed for the inventory through either emissions reports or interviewing the workers at the facility. Below is a flow chart describing the processes involved in the treatment, how they are linked and some of the inputs and outputs of each process.

To get the mass balance right in the above-mentioned system, some educated assumptions about densities for different compounds were made. These are shown in table 5.1. The slop water is received at the docks and put into tanks where it can settle. The heaviest particles sink to the bottom through gravitational separation. The system could be split in two, one flow of water and one flow of mud, but since the two interact with each other on several processes, the system is viewed as one whole system.

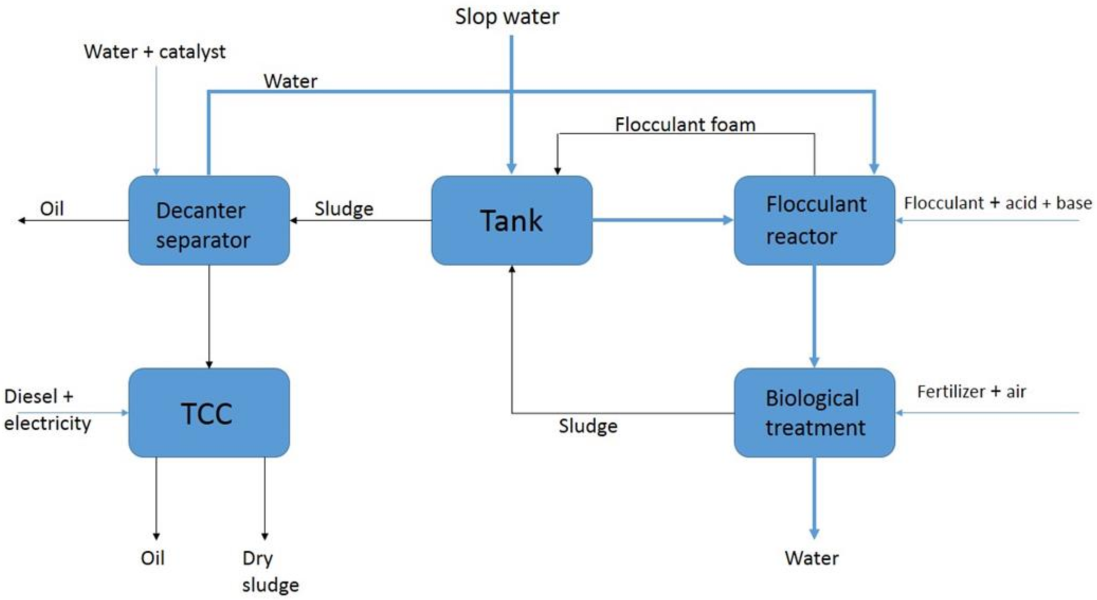


FIGURE 5.3: SCHEMATIC OF THE ONSHORE TREATMENT PROCESS

5.3.1 TRANSPORT

Based on the statistics over where the slop was received from in 2012, provided by Halliburton, the table underneath was extracted. Transportation of the slop is executed in two parts: from offshore field to respective onshore base and from base to treatment facility. The three onshore bases Kristiansund, Florø and Dusavik were the most frequently used bases. The average distances from oilfield to onshore base, and from base to the treatment facility at Mongstad were calculated based on the mass percentages of transport. The average distance values were used in the inventory.

TABLE 5.3: TRANSPORTATION OF SLOP TO MONGSTAD

Onshore base	Distance to Mongstad	Corresponding Oilfield	Distance to onshore base	Percentage of totalt transport by mass
Kristiansund	600 km	Heidrun + Åsgard	190km	18%
Florø	200 km	Snorre	150 km	71%
Dusavik	250 km	Gudrun	220 km	11%
Average distance traveled	271 km		163 km	

SUPPLY VESSEL

The MISA process «Operation, offshore supply vessel» models the transportation of slop from oilfield to onshore base. This process is useful here because it uses tkm units, and the total mass that needs transport is given, as well as the average distance travelled. Embedded in this process is the consumption of heavy fuel oil, the emission to air associated in the combustion of the fuel and the incineration of the bilge oil waste.

CARGO VESSEL

The MISA process «Cargo transport» was used in the model for the transportation from onshore base to Mongstad. Inputs to this process are the combustion of marine diesel oil, port maintenance, construction of port facilities and maintenance. This vessel may be too large for this task, but still applicable because of the port construction processes included which have been omitted from the infrastructure of the treatment facility, though picked up here. The length of transportation is the average distance from table 5.3 and the mass is given by Halliburton.

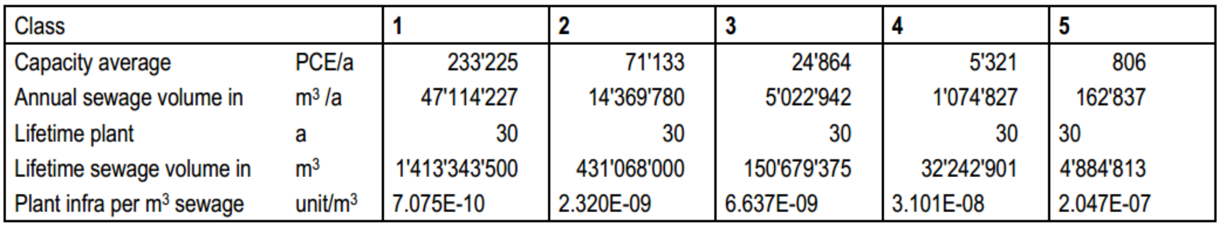
LORRY

The absolute final step of the transportation is the transport of waste from the treatment to landfill and hazardous waste treatment. The closest place to send both types of waste produced at the facility, is only 17 km away, and the mass of the total waste was provided by Halliburton. The process «Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}|market for| Alloc Def, U», found in the Ecoinvent database, is used in the model for this transport. This lorry is medium sized and comparative to the ones observed on site.

5.3.2 INFRASTRUCTURE

The infrastructure for a wastewater treatment plant was found in Ecoinvent, «Wastewater treatment plant, class1/CH/IU». This process is based on a sewage treatment plant, but it is assumed to be a close enough facility that it can be used in this context. The background reasoning for choosing class 5, was found in the Ecoinvent manual for wastewater treatment. The properties of this class of wastewater treatment plant was the closest resembling the facility at Mongstad.

TABLE 5.4: CALCULATION OF INFRASTRUCTURE UNITS PER M^3 SEWAGE



Class		**1**	**2**	**3**	**4**	**5**
Capacity average	PCE/a	233'225	71'133	24'864	5'321	806
Annual sewage volume in	m^3 /a	47'114'227	14'369'780	5'022'942	1'074'827	162'837
Lifetime plant	a	30	30	30	30	30
Lifetime sewage volume in	m^3	1'413'343'500	431'068'000	150'679'375	32'242'901	4'884'813
Plant infra per m^3 sewage	unit/m^3	7.075E-10	2.320E-09	6.637E-09	3.101E-08	2.047E-07

Table 5.4 shows the properties of the different classes of wastewater treatment plants in Ecoinvent. The most relevant class for the treatment facility on Mongstad is the fifth class, based on the amount of annual processes volume which is (40223-15474) for the Mongstad facility. The lowest value in the class is larger than that, but applicable. To determine the fraction amount of "wastewater treatment plant" needed in the inventory the value for plant infrastructure per m^3 sewage was multiplied with the amount of slop in to the facility (Doka, 2003).

The chemical factory infrastructure needed for the chemicals used in the treatment was a generic chemical plant, scaled to fit the mass of chemical output (Althaus et al., 2007).

5.3.3 ENERGY USE

The facility uses only electricity for their energy needs. A large amount of the energy goes to the TCC and has a huge influence on the total amount of energy used. The table below shows the distribution of energy to the different processes in the system.

TABLE 5.5: ENERGY USE OF THE DIFFERENT PROCESSES

Process	Estimated energy use	Comment
TCC	846 MWh	The TCC uses 700kW to process 3 tonnes sludge an hour, leading to 233 kWh/ton. Multiplied by the tonnes of input to the unit, 3662 tonnes (Termtech).
Decanter separation	47 MWh	A typical decanter uses 1-2kWh/tonnes water removed and that tricanters use a little more (Roger Khalil 2007). The energy consumption has therefore been set to 3kWh/tonnes water removed.
Biological treatment	52,5 MWh	The electricity need is for 10 compressors injecting hot air into the biological tank. The Ecoinvent library has several processes concerning compressed air generation, and the average of all the «Compressed air, average generation» is approximately 0,15kWh/m^3. The average value is used because of lack of information on the type of compressor used. The compressed air is needed for continuous circulation of the water, and keeping the temperature constant while the heat escapes from the top of the tank. Estimated volume of compressed air is 40 m^3/h/yr.
Flocculation and flotation	21,12 MWh	The energy use of the DAF was estimated from an existing process from the MISA library, «Water treatment, dissolved air flotation, onshore» (MISAtest39325500402), which states an energy use of 0.33kWh/m^3. Assumed need for dissolved air in the process is the same as the volume of input to the process.
SUM	966,62	MWh

An average value for energy use in office buildings is 200 kWh/m^2/yr (SSB, 2009) (enova, 2011), and the Mongstad facility has an estimated 200m^2 of office space, which sums up to 40 MWh. Additionally lighting, operating pumps and other hydraulic machinery needs energy to. The estimated energy uses for the processes may be on the conservative side and will fluctuate according to season and the quality of incoming slop. If the water content going to the TCC increases, its energy requirement will increase substantially. Since this inventory is seen over the course of a year, the energy use will vary through this period.

5.3.4 CHEMICALS

The flocculants used in the decanter separation and the flocculation process were only stated with product name and a safety data sheet. If the composition of the chemicals shows a percentage interval in the ingredients declaration, the middle value in this interval was chosen. In the cases where the sum of the components did not equal a hundred percent, the assumption was that the rest is generic tap water. In addition, the TCC uses diesel as a blocking fluid to prevent the TCC from clogging during operation

TABLE 5.6: CHEMICALS USED, BY GIVEN WITH PRODUCT NAME, FUNCTION AND THEIR SUBSTITUTION

Product name	Content	Function	Process in SimaPro
Nalco, ULTIMER 7752	Cationic polymer: polyacrylamide	Flocculant, used in decanter	Polyacrylaimide, at production» A process made by MISA (MISAtest39325500223).
Unifloc AE 300	Polymers	Flocculant, used in flocculation	Se own inventory, Appendix C 2
STRUKTOL SB2080	Fatty acids from vegetarian oil, and fatty acohol	Antifoam, used in biological treatment	Se own inventory, Appendix C 2
BAC 50	Benzalkonium chloride	Surfactant, used in flocculation	«Benzal chloride, at plant/RER U» (EIN_UNIT08484306926)
Flex-Bio 10-7	Phosphoric acid, Sulphuric acid	Fertilizer, used in biological treatment	Se own inventory, Appendix
Sodium Hydroxide	NaOH	Base, pH regulator used in flocculation	Sodium Hydroxide 30%»
Iron(III)chloride	Fe3Cl	Flocculant, used in flocculation	Iron(III)chloride, 40% in H2O, at plant/CH
Hydrochloric acid	HCl	Acid, pH regulator used in flocculation	Hydrochloric acid, 30% in H2O,at plant/RER U
Diesel	Petrodiesel	Blocking fluid in TCC	Diesel at regional storage/RER U

5.3.5 DIRECT EMISSIONS

The direct emissions are reported to a database as the law states. The emissions include BETX, TOC, oil and many different metals. The direct emissions vary in accordance with the quality of the incoming slop water, and the accompanying adjustments done in the treatments process to handle it. To get the model to signify an average onshore treatment facility the average value of the Mongstad treatment facility combined with a similar facility in Tanager operated by SAR, over two years was used. The emission values of the specific substances and the resulting average emitted among per m^3 slop.

TABLE 5.7: DIRECT EMISSIONS FROM TWO ONSHORE TREATMENT FACILITIES, THEIR COMBINED AVERAGE AND EMISSION PER M^3.

Kg pr år	**Halliburton Mongstad**			**SAR Tananger**			**kg / m^3**
	2011	**2012**	**Average /m^3**	**2011**	**2012**	**Average /m^3**	
Arsen	0,38	0,82	4,8487E-05	0,25	0,14	2,3972E-05	3,62E-05
Barium	36,9	15,64	0,00212291	62,6	47,48	0,00676624	4,44E-03
BTEX			0	0,58	0,15	4,4871E-05	2,24E-05
Lead	0,05	0,05	4,0406E-06	0,11	0,29	2,4587E-05	1,43E-05
Cadmium	0,01	0,02	1,2122E-06	0,03	0,01	2,4587E-06	1,84E-06
Chromium	0,96	0,91	7,5559E-05	0,33	0,63	5,9008E-05	6,73E-05
Copper	2	1,08	0,00012445	0,53	0,33	5,2861E-05	8,87E-05
Molybden	1,04	2,59	0,00014667	2,25	6,86	0,00055996	3,53E-04
Nickel	11,92	11,85	0,00096044	3,5	2,88	0,00039216	6,76E-04
Oil	260	20	0,01131359	50	60	0,00676133	9,04E-03
Zink	**2,29**	**0,8**	0,00012485	**2,57**	**1,496**	0,00024992	1,87E-04
Tin	0,42	0,47	3,5961E-05	0,21	0,19	2,4587E-05	3,03E-05
TOC	28600	11150	1,6061255	13750	12220	1,59628742	1,60E+00
Vanadium	0,37	0,61	3,9598E-05	0,14	0,08	1,3523E-05	2,66E-05
production volume	24749			16269			

In table 5.7 the direct emissions for the offshore treatment per m^3 of incoming slop is calculated from the production levels that year, provided by norskeutslipp.no. The production volume for each treatment facility used is the one reported from 2012, because no value for 2011 was available. It is believed that the production volume is comparatively the same.

5.3.6 DISPOSAL

There are two waste flows in the model of the system: the dried sludge from the TCC and the low grade oil. The disposal of these is included in the model for the onshore treatment, although it is not a part of the actual treatment facility. The oil goes to hazardous waste disposal, which means burning it, and the dry sludge goes to landfill. The appropriate substitution for dried sludge waste was found to be a generic waste process with little water in it: «Disposal, inert waste, 5% water, to inert material landfill/CH U». The disposal process for the low grade oil was chosen to be «Disposal, used mineral oil, 10% water, to hazardous waste incineration/CH U», in lack of more information about the handling of this hazardous waste. This disposal process entails burning of the oil. A more environmentally friendly way of disposing of the oil would be incineration with thermal recovery.

5.4 OFFSHORE TREATMENT

Offshore treatment is a slop treatment scenario that is connected to onshore treatment. The residue sludge from the treatment offshore is hazardous waste and needs further treatment and transportation to an onshore facility. To look at only the offshore treatment might be tempting, but it would be a false representation of the required efforts to treat the slop. The whole chain of processes, transport and onshore sludge treatment is included in this scenario.

There are many different practises and processes used in the treatment of slop offshore. Therefore, it is difficult to choose one particular process to indicate how slop is treated offshore. According to discharge reports from owners of oilfields on NCS to Norwegian Oil and Gas Association, the two most common technologies used in drilling operations in 2012 are a mechanical separation sequence and a DAF with flocculation. These two technologies are examined as part of this scenario, and are depicted by the flowcharts in figure 5.4 and 5.5.

5.4.1 OFFSHORE, MECHANICAL SEPARATION TREATMENT

This treatment process avoids using chemicals and can handle 5-10 m^3/hour (Miljødirektoratet, 2013c). According to Baker Hughes» website, a supplier of this type of technology, oil can be retrieved from the treatment, by installing a tricanter instead of a decanter. Another supplier, GEA Westfalia, also present this alternative in their mechanical separation equipment. This extra equipment will make it possible to recover oil from the waste and use it in the drilling fluid or mix it with crude oil. The estimated reduction of the slop volume is set to be 70% which is an approximation from the field specific emission reports for 2012 (Norsk Olje og Gass, 2012). For this inventory model the standard two phase decanter will be used. Oil recovery is performed onshore, during the TCC process.

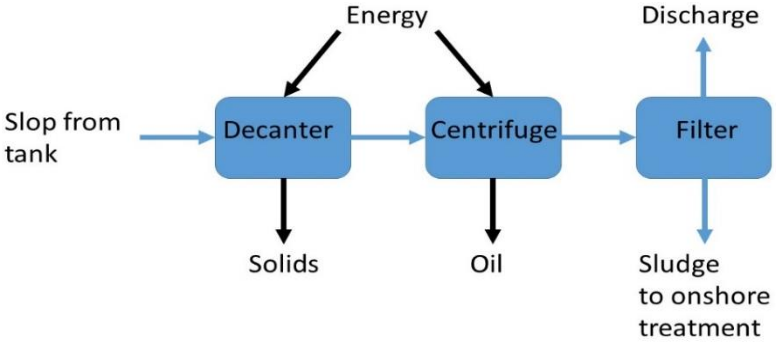


Figure 5.4: Mechanical separation of slop, offshore

DECANTER

The decanter uses energy both for the separation process and a feed pump for slop input. The process in the inventory for providing this energy is called «Diesel, burned diesel-electric generating set/GLO,U» from the Ecoinvent database. The feed pump is assumed to a mono feed pump with a capacity of 0.75 kW, used for 6 hours a day to pump a volume of 60 m^3 per day. This set of assumptions leads to an electricity use of 0.08 kWh/m^3. The decanters' energy use estimate is based on a 30 kW decanter where only 20 kW is absorbed for treating the mentioned slop volume. The pumps electricity consumption is calculated by using the formula, applied to all the pumps in the inventory: $\frac{Power\ [kW] \times Time\ [hours]}{Waste\ water\ flow\ [m^3/day]}$

CENTRIFUGE

In this case the centrifuge is a disc stack separator. The pump for transporting the slop from the previous process to the separator inhabits the same assumptions and energy consumption as the one for the decanter. Estimated energy consumption for the disk stack is based on a separator with a 5kW capacity, where only 4kW is absorbed to treat 40 m^3 of slop in 6 hours. The volume of slop is reduced by a third from the preceding decanter separation. The process used to model this energy is still «Diesel, burned diesel-electric generating set/GLO,U».

FILTER

An oil absorbing filter cartridge from Twinfilter weighs 0.5 kg, consists of about 90% polypropylene and has the capacity of removing 2 kg of hydrocarbons (Twinfilter). Two kg of oil relates to approximately 2 m^3 of slop with an oil content of 1000ppm, therefore will half a cartridge suffice per m^3 of slop. In the model, the entire mass of the cartridge is assumed to be polypropylene in lack of specifications on the remaining 10% of the cartridge. This simplification is assumed to have no influence on the final results.

5.4.2 OFFSHORE, FLOTATION SEPARATION TREATMENT

Halliburton delivers an offshore treatment unit such as this and reports a reduction of slop water as high as 60-80%. According to Wärstilä, another supplier of this type of technology, such a system will reduce the volume of slop by 80-90%. In an annual emissions report Statoil claims a reduction rate of a whopping 90% by using Halliburton's slop unit. In the inventory, the middle value of these intervals is chosen: 80%. This means that 20% of the slop becomes sludge and will be transported onshore.

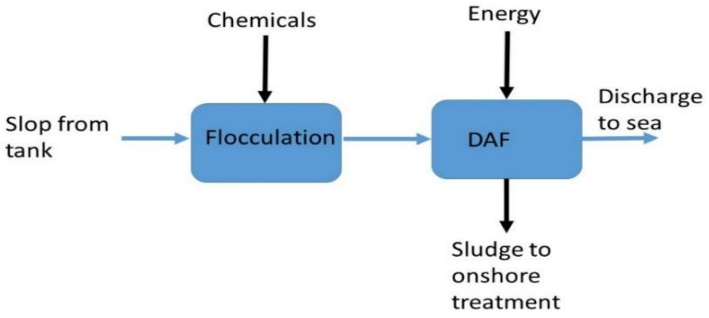


FIGURE 5.5: FLOCCULATION AND FLOTATION SEPARATION OF SLOP, OFFSHORE

FLOCCULATION

The chemicals used in the coagulation and flocculation process are based upon literature concerning oily water treatment and the inventory by Anthony Okiemute, and differ from the ones used for the same purpose onshore. This shows that there are not one way of solving the slop water problem, and that there are different practises on different locations. Offshore it might be beneficial to not ship and store that many different chemicals on the rig while onshore treatment can do this. «Aluminium sulphate, powder, at plant/RER U» is a primary coagulant frequently used in the treatment of industrial wastewater. An average value from several different articles of 0,12 kg/m^3 is used in the inventory (Puszkarewicz, 2008, Eckenfelder, 1989, Thamer et al., 2007, Sharaai et al., 2009). Bentonite clay is composed of inorganic minerals and adsorb a wide variety of contaminants, a value of 0,005 is an average value from the literature(Armenante, Puszkarewicz, 2008). «Bentonite at processing/DE U» is the Ecoinvent process used in the inventory for this. Sodium Hydroxide, NaOH, is used to regulate the pH of the water as a catalyst for the chemical reactions to make flocs, average value from the literature gives 0,03 kg/m^3 is used (Thamer et al., 2007, TAUD, 2003, Al-Ani, 2012)The Ecoinvent process «Sodium hydroxide, 50% in H2O, production mix, at plant/RER U» is used in the inventory for this chemical. To dose the chemicals into the slop water, a dosing pump running on electricity is used. Two 0,19 kW pumps are assumed used for 2 hours a day for dosing illustrated in the inventory by the process «Diesel, burned diesel-electric generating set/GLO U».

DAF

After the flocculation the flocs are separated from the water through dissolved air flotation. No chemicals are added at this stage, only electricity for the compressor and skimmers. The process in the inventory for tis energy use is «Diesel, burned diesel-electric generating set/GLO U», and the value of 0,207 kWh/m^3 is based on literature on DAF and a DAF process in the MISA database, MISA library: «Water treatment, dissolved air flotation, onshore» (MISAtest39325500402): 0,33kWh, (Vlasopoulos et al., 2006): 0,221kWh/m^3, (Johnson et al., 2009). Average between all these values in 0.207 kWh/m^3.

5.4.3 DIRECT EMISSIONS

The direct emissions from the treatment of slop water offshore, are identical to the direct emissions from the onshore treatment facilities at Tanager, operated by SAR, and Mongstad operated by Halliburton, discussed in chapter 5.3.5. This decision is rooted in the emission reports from NOGA, whom describe emissions well under the given permissions and they resemble the emission permission for onshore activities. This data is used because of lack of complete emission information from offshore slop treatment. The offshore TOC emission values are similar to the onshore values and are therefore considered comparable as much of the pollution sits in the oil part of the slop. As the reported values from norskeutslipp.no shows, the amount of emission and even the substances emitted vary. This is due to the fluctuation in quality and composition of the incoming slop, resulting in adaptations in the treatment process. Corrosion of galvanised equipment may be a source of zinc and lead in the discharged water (Scurtu, 2009).

Indirect atmospheric emissions take place at all stages of oil and gas industry’s activities. The main sources of these emissions include burning of gas and excessive amounts of hydrocarbons during well testing and development, flaring to eliminate gas from the storage tanks, combustion of fuel in the energetic units, evaporation or venting of hydrocarbons during different operations. These emissions are included in the background processes.

5.4.4 TRANSPORT ONSHORE

After the processing on the rig, there is still some waste left which needs to be transported to an onshore facility for proper end-treatment and disposal. Shipping the sludge to shore includes craning the slop tank onto a supply vessel, craning it onshore onto another boat that takes it to the treatment facility.

CRANES

There are two cranes in the transportation process, one on the rig and possibly one on the receiving dock. The cranes use 19.9 horsepower hours per metric ton, which is equal to 14,84 kWh per ton. By using the densities provided in table 4,1 one m^3 of slop equals 14,99 kWh/ m^3 (James and Rørvik, 2002).

SUPPLY/CARGO VESSELS

The MISA process «Far serenade, at economy speed (11,3kn)» was used as the offshore supply vessel used for oilfield to onshore base transportation. This specific vessel was chosen because it has the middle value fuel consumption in the MISA supply vessel catalogue. In lack of specifications as to which supply vessels were used, the average will suffice. The input to this transportation process is just energy in the form of the process «Combustion of marine diesel oil, on offshore supply vessel at sea». This process includes diesel consumption and the emission to air correlating to its combustion. To calculate the operating time the travelling speed of 11.3 knots was converted to 21 km/h and divided by the average distance from oilfield to onshore base, times 2 for the trip back, resulting in 15,5hours. This value is divided by the slop handling capacity of the vessel, 2500 tonnes, to get the value for 1 m^3 of slop.

TRANSPORTATION TO LANDFILL

Transportation of the waste to the nearest landfill for hazardous waste, which is located only 17 km from the treatment, is done by trailer. Oil from the TCC unit is sold as light fuel oil.

5.4.5 ONSHORE END-TREATMENT AND DISPOSAL

Once the sludge is in the onshore treatment facility it undergoes further treatment before it is disposed in a landfill. These end-treatment processes include a decanter separator and a TCC unit. In other words, they are the same processes found in the onshore inventory for the sludge processing. Even though the processes are the same the input is no longer the same. the concentration of the pollution in the slop has increased, in other words there is less water in the sludge than in the slop. This leads to an alteration of the outputs of the treatment processes onshore. In the onshore scenario the water content in the input to the decanter is close to 60%, and water is added in this process resulting in almost 70% of the output from the decanter is water which goes through the water treatment in the facility. For this scenario, the water content is reduced by half to take into consideration the primary treatment taken place offshore. This results in higher disposal and recovery rates per input to the sludge treatment than for the onshore scenario.

DECANTER

This decanter inventory is the same as for the onshore scenario. This decanter process uses an organic polymer to enhance the separation, in the inventory this is a MISA process called «Polyacrylamide, at production». It includes energy in the form of heat, the production of acrylonitrile and a little tap water. To dilute this chemical a large amount of tap water is used. To operate the decanter electric energy is used in the form of the Ecoinvent process «Electricity, low voltage, production NO, at grid/NO U». An estimated water concentration in the incoming slop is 30%, which will be separated out. The rest of the sludge is assumed to contain 50% oil and 50% solids. 35% of the input goes to disposal and another 35% goes through to the TCC unit.

TCC

This TCC unit has the same inventory as the one in the onshore scenario. It treats the sludge from the decanter process, and is the last processing the slop undergoes. A lot of energy is needed to operate this equipment and electricity is used for this, «Electricity, low voltage, production NO, at grid/NO U». The energy consumption of this process is derived from interviews with the staff at Mongstad treatment facility and product specifications from the supplier, resulting in a consumption of 233 kWh/ton input. Diesel is introduced to the process not as a fuel, but as an anti-clogging chemical, 300 litres a day. Outputs of the TCC process are water vapour released to air, dried sludge going to landfill and recovered oil. This oil is resold as light fuel oil and this output is the reason for the negative impacts in the scenarios including a TCC. The outputs of this process are water vapour, which constitutes 10%, dried sludge going to landfill, which is 60% of the input and fuel oil making up the rest.

6 LIFE CYCLE IMPACT ASSESSMENT

Presented in this chapter are the processed results from the life cycle impact assessment, which is briefly described in chapter 4.3.1. Each scenario's impact results are presented, and then they are compared to one another. The impact assessment will focus on the six selected impact categories, specified in chapter 4.3.1. The mid-point approach is used in each scenario, meaning that the environmental impacts refer to damage potential.

The selection of impact categories in this chapter are chosen because they have special significance for this system and are used to evaluate the general performance of the scenarios. Marine ecotoxicity is an important impact category important because the direct emissions are all emitted to sea. Human health is a category of great concern, because it concerns ourselves directly. Climate change, particulate matter formation and ozone depletion were chosen because they are interlinked and show different perspectives of fuel combustion for energy, which is a big part of this system. The ability to recover oil within the system has a large impact on the fossil depletion impact category, and is therefore an important category for illustrating this aspect of the system.

6.1 LIFE CYCLE IMPACT ASSESSMENT OF INJECTION SCENARIO

Figure 6.1 shows the environmental impacts for the injection scenario, with functional unit 1 m^3, for the six selected impact categories.

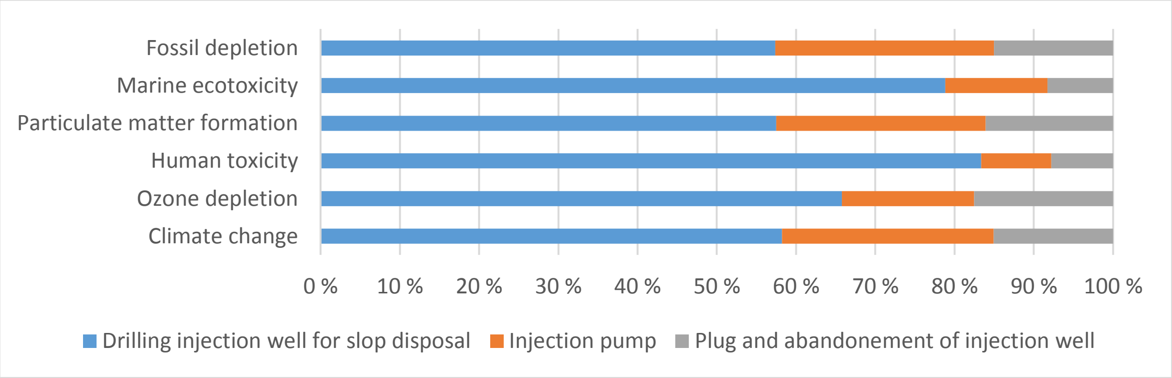


FIGURE 6.1: IMPACT ASSESSMENT OF INJECTION SCENARIO, AGGREGATED

Looking at figure 6.1, depicting the impact assessment of the injection of slop scenario, it is clear that the main contributor is the drilling of the injection well itself. The operation of the injection as well as the end of life treatment, leaves much less impact. If an abandoned well is utilized instead, it would alter the picture drastically, eliminating the impacts associated with the drilling. This is in accordance with Saasen's findings in his article about energy use in slop handling. Saasen proclaims that it is the drilling rig who is responsible for most of the impacts related to slop injection.

6.1.1 LIFE CYCLE IMPACT ASSESSMENT OF DRILLING AN INJECTION WELL

Figure 6.2 zooms in on the main contributor in the injection scenario, drilling the injection well. Disaggregating the processes involved and assessing their impact contribution, facilitates further insight into the impact contributors.

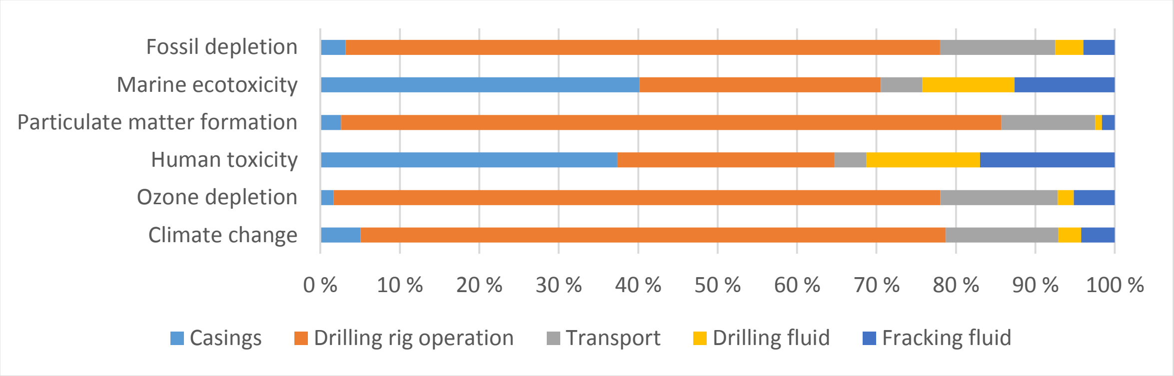


FIGURE 6.2: IMPACT ASSESSMENT OF DRILLING AN INJECTION WELL

Within the well drilling process, it is the rig that contributes the most, followed by the construction of casings. The drilling rig has a large presence in all the impact categories, but greatest in the fossil depletion, ozone depletion, climate change and particulate matter formation categories. These categories are closely linked to the rigs tremendous use of fuel and the combustion of it. This process will be more closely examined further in the chapter. Transportation in the figure is helicopter flights and use of supply vessel, and is not a major contributor in this system, dwarfed by the huge fuel consumption of the drilling rig.

In the figure the three different casings are grouped together, but the 16” casing is responsible for most of the impact because it is the longest section. Well casings are made of steel and cement, and steel production is the main impact contributor for all the casings.

The chosen drilling fluid, Gydril, is not a main contributor, but this need not be true for all drilling fluids. The choice of drilling fluid can shift the impact assessment either way. The literature on drilling waste emphasizes the importance of using more environmentally friendly drilling fluids, and this scenario model is no different. When using a more environmentally harmful WBM found in the MiSA process inventory; Performadril, it overwhelms the other processes in the impact assessment. This proves the crucial importance of the drilling fluid used. This aspect of the model is further explored in a sensitivity analysis in chapter 7.2.

6.1.2 LIFE CYCLE IMPACT ASSESSMENT OF OPERATING THE DRILLING RIG

A closer look at the operation of the drilling rig shows that the production of diesel consumed during drilling is the main contributor for the operation of rig. Construction of the rig and raw materials needed for it is not included in the process. The inclusion of the construction would increase the impacts from this process, but not by much, because of the long life of the equipment and allocation between all the drilling missions through this lifetime. Direct emissions from burning of diesel in the generator is the second largest contributor in the operation of the rig, and is particularly prominent in the climate change and particulate matter formation. Both impact categories are closely linked to fossil fuel combustion.

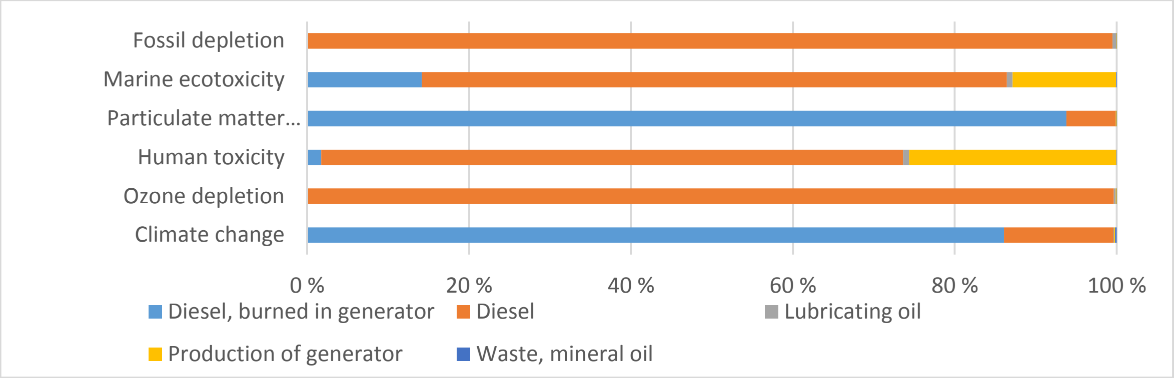


FIGURE 6.3: IMPACT ASSESSMENT OF OPERATION OF DRILLING RIG

6.2 LIFE CYCLE IMPACT ASSESSMENT OF ONSHORE TREATMENT SCENARIO

The results from the impact assessment for the onshore treatment scenario is presented in figure 6.4. The impact assessment for the onshore slop treatment is more complex than the injection scenario's assessment, due to several more processing stages and the use of many different chemicals.

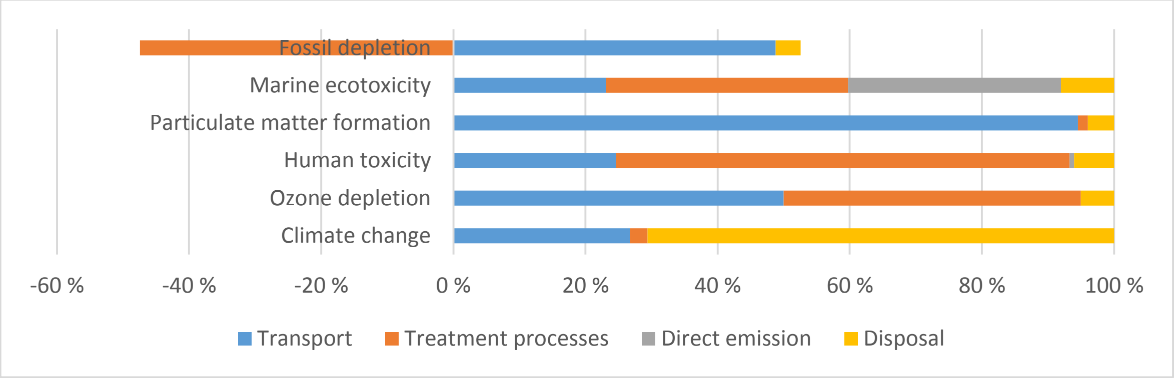


FIGURE 6.4: IMPACT ASSESSMENT OF ONSHORE TREATMENT, AGGREGATED

Unlike in the injection scenario, there are negative impacts present in this scenario. This is a result of the oil recovered in the TCC unit, which is reused as fuel oil. This recycling reduces the need for producing fuel oil from scratch, thus saving the environment from the related impacts. The negative impacts show up in the fossil depletion and ozone depletion. All these categories are connected to the extraction of crude oil and refining processes to make an oil product. The direct emissions emitted to the ocean, have a noticeable effect on the marine ecotoxicity category.

The impact assessment shows that transport is a large part of the impacts connected to this scenario. Which is expected, because of the large volumes of waste transported by boat and the industry wanting to treat the slop offshore on a rig to save transport costs. Transportation is a contributor in all the impact categories and most noticeably in the particulate matter formation category. This is due to the VOCs released from the combustion of diesel. In figure 6.4, all the different legs of transportation are aggregated into a single transportation process. Further inspection into the transportation impacts reveals that the largest contributor is the cargo transport. This is in accordance with expectations due to the fact that this is a large vessel requiring plenty of fuel. Next in the ranking of contributors is the supply boat. The contribution from the transportation on land is almost negligible, because of its relatively short distance.

In the climate change category, disposal is the largest contributor by far. The disposal process is aggregated from the disposal of the dried sludge going to landfill and the low-grade oil, which is incinerated. This incineration causes the large impact in the climate change category by burning oil, which releases greenhouse gases in abundance. When juxtaposed with processes only using electricity with Norwegian electricity mix, this release of GHGs is much larger than in any of the other treatment processes. The only other contribution in this category is transportation, since the vehicles burn fossil fuel for energy.

Dividing the treatment process into the individual processes featured, tells us about how the impact is partitioned between them. The results from this is shown in figure 6.5. The process of flocculation and flotation requires many different chemicals and in considerable amounts. That is why this process is the main impact contributor in all categories.

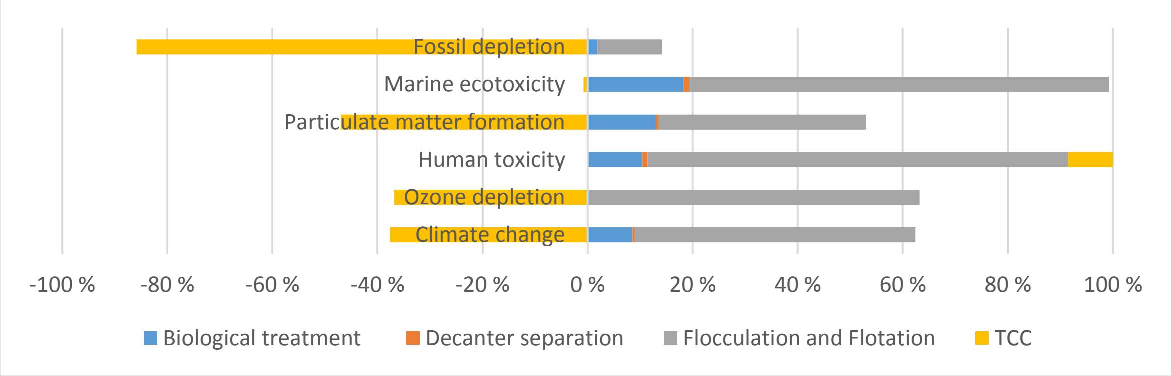


FIGURE 6.5: IMPACT ASSESSMENT OF ONSHORE TREATMENT PROCESSES

On the negative impact side, the TCC process is the only contributor. This negative impact is interpreted as beneficial for the environment. This is a result of the impacts of the inputs to the TCC unit being minor to the benefits of the retrieved oil. This process undergoes further examination in the next chapter.

The decanter uses very little energy compared to the other treatment processes and small amounts of chemicals. Figure 6.5 tells us that the impacts from this process is negligible compared to the other processes in the treatment. In another perspective, this process produces the oily waste that goes to incineration, which has a large impact on the impact of the whole system, as seen in figure 6.4. Hence, there may be an incentive to increase the efficiency and inputs to the decanter so it produces less waste. This addition of efforts in the decanter process may be beneficial when looking at the big picture, if the incineration of the oil decreases.

6.2.1 LIFE CYCLE IMPACT ASSESSMENT OF THE TCC PROCESS

The TCC process provides negative impacts because of the recovery of oil from the waste, as seen in figure 6.6, depicting the impact assessment of the TCC process. The oil is used as heating oil, eluding the need for production of this fossil fuel, which has high environmental impacts.

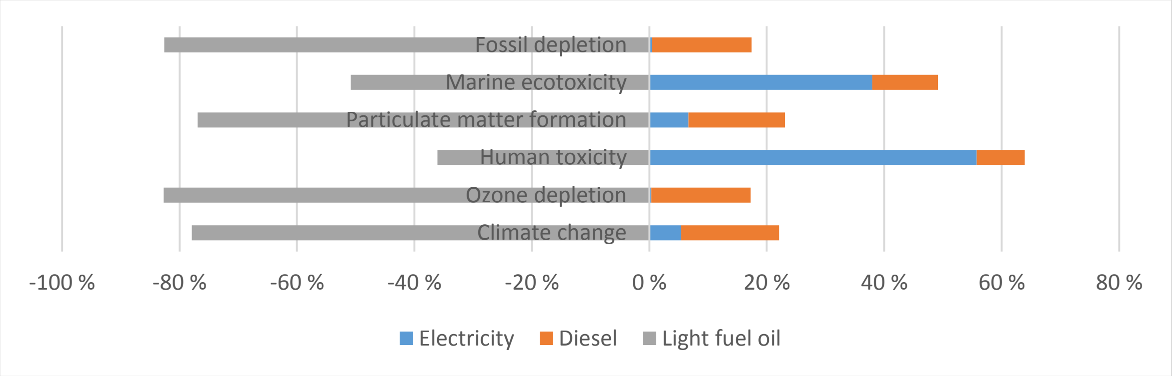


FIGURE 6.6: IMPACT ASSESSMENT OF THE TCC PROCESS

The diesel used as blocking fluid, has the largest impact in categories linked to the extraction of fossil fuels; ozone depletion, natural land transformation and fossil depletion. The volume of diesel used in the process is relatively small and the use of electricity is an overall larger contributor to the environmental impacts. The use of electricity tremendous, yet as figure 6.4 shows, the benefits of the recovery of oil is larger than the impact though operation in 5 out of 8 categories. The impact categories suffering from this process is human toxicity, marine ecotoxicity and freshwater eutrophication.

6.2.2 LIFE CYCLE IMPACT ASSESSMENT OF THE FLOCCULATION AND FLOTATION PROCESS

Figure 6.7 shows the results from the impact assessment of just the flocculation and flotation process. The use of iron(III)chloride affects the impacts from the flocculation and flotation process profoundly because of the extensive use of the chemical. A staggering 360 tonnes of the chemical is used per year compared to the second largest volume of 800 kg of UNIFLOC AE 300, another flocculating agent. A comparison of the impact of all the chemicals used in the flocculation process is presented in appendix C. It shows that benzal chloride is the most environmentally harmful per kg. Iron(III)chloride is the second most harmful chemical, closely followed by hydrochloric acid. Reducing the use of iron(III)chloride will reduce the overall environmental impact of the process and system.

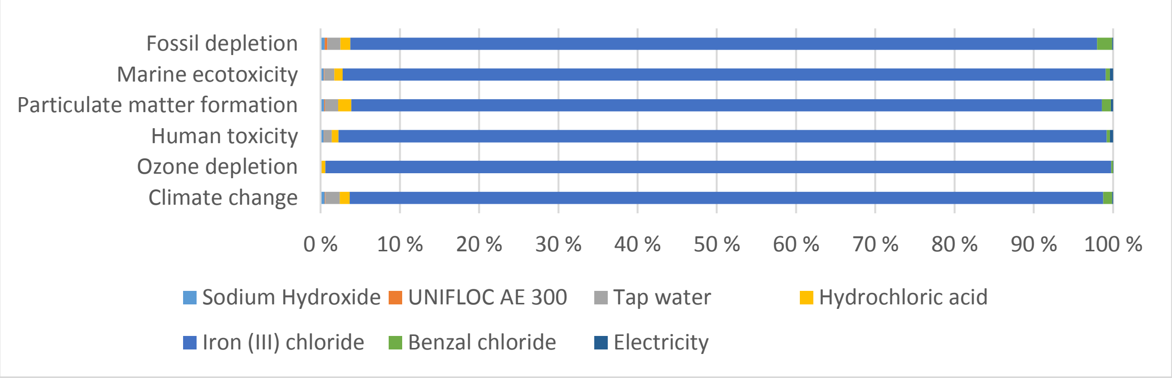


FIGURE 6.7: IMPACT ASSESSMENT OF THE FLOCCULATION AND FLOTATION PROCESS

6.3 LIFE CYCLE IMPACT ASSESSMENT OF OFFSHORE TREATMENT SCENARIO

The two different approaches to offshore treatment are flotation based and mechanically based. After the offshore treatment the slop undergoes the exact same processing in both scenarios, a decanter separation and a TCC process. The only difference is in the amounts of slop being shipped and treated onshore.

6.3.1 LIFE CYCLE IMPACT ASSESSMENT OF OFFSHORE FLOTATION SEPARATION SCENARIO

The flotation based treatment consist of a DAF process following a flocculation. This technology has a high efficiency in reducing the slop water volume by 80%. Figure 6.8 depict the results of the impact assessment of offshore flotation treatment followed by transport onshore and the end treatment.

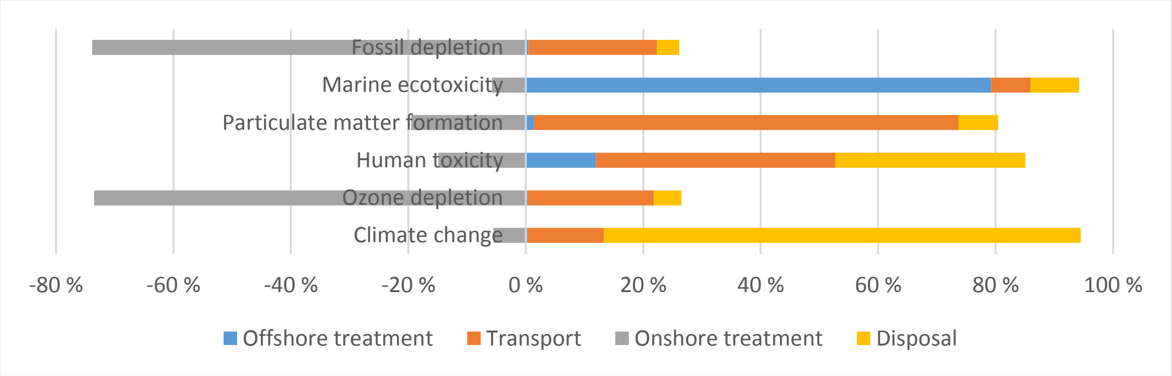


FIGURE 6.8: IMPACT ASSESSMENT OF OFFSHORE TREATMENT, FLOTATION SEPARATION SCENARIO

Just as in the impact assessment for onshore treatment, there are negative impacts resulting from the TCC’s oil recovery here. The direct emissions take place out at sea and makes a generous contribution in the marine ecotoxicity impact category. The disposal processes are the same as for the onshore scenario and are major contributors in climate change and freshwater eutrophication, for the same reasons. In the offshore treatment, it is the flocculation that contributes the most impact, just like for the onshore equivalent process.

6.3.2 LIFE CYCLE IMPACT ASSESSMENT OF OFFSHORE MECHANICAL SEPARATION SCENARIO

The impact assessment for offshore mechanical treatment technology is exhibited in figure 6.9. This impact assessment shows many similarities with the flotation based offshore scenario, since the only difference is in the primary treatment. When closely inspected it is apparent that the mechanically based treatment makes a slightly larger impact than the flotation based.

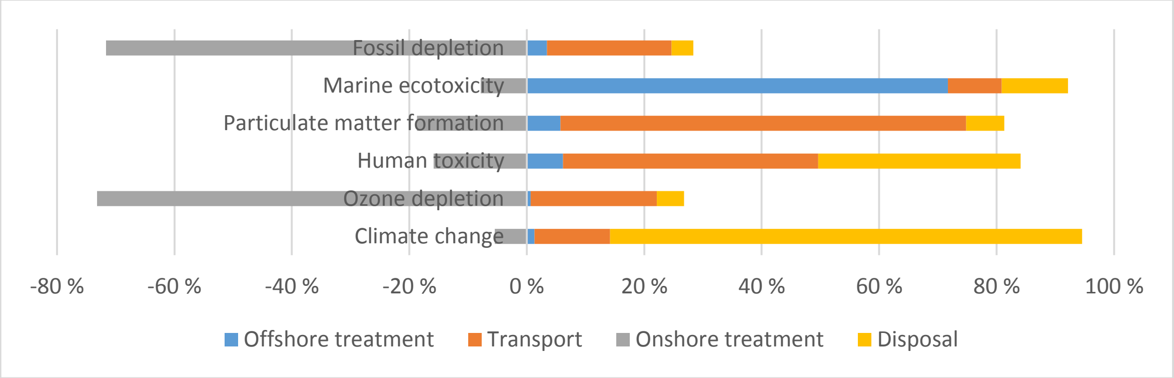


FIGURE 6.9: IMPACT ASSESSMENT OF OFFSHORE TREATMENT, MECHANICAL SEPARATION SCENARIO

The two alternatives are juxtaposed in figure 6.10, to clearly disclose their difference in impacts. The distinguishing factor between them is the amount of slop that needs transportation and the amount of recovered oil. In the flotation separation scenario, less slop is transported onshore and less oil is recovered. The mechanical separation generates more transportation needs because of lower reduction efficiency, but more oil is recovered. These two parameter properties are conflicting. A larger volume for transport increases the impact, but since more slop finds its way to the TCC, more oil is recovered. This paradox is displayed in figure 6.10, by the larger impact for the mechanical separation, both in negative and positive manners. This is a result of the assumption that the quality of the slop from the offshore treatment is the same for both scenarios. This might be a faulty assumption, but might also take into consideration the fluctuations of the quality of the slop in the first place.

The main thing to take away from this comparison is that the main cause of impact is the transportation and the use of the TCC unit. These are the most influential processes, not the offshore treatment itself.

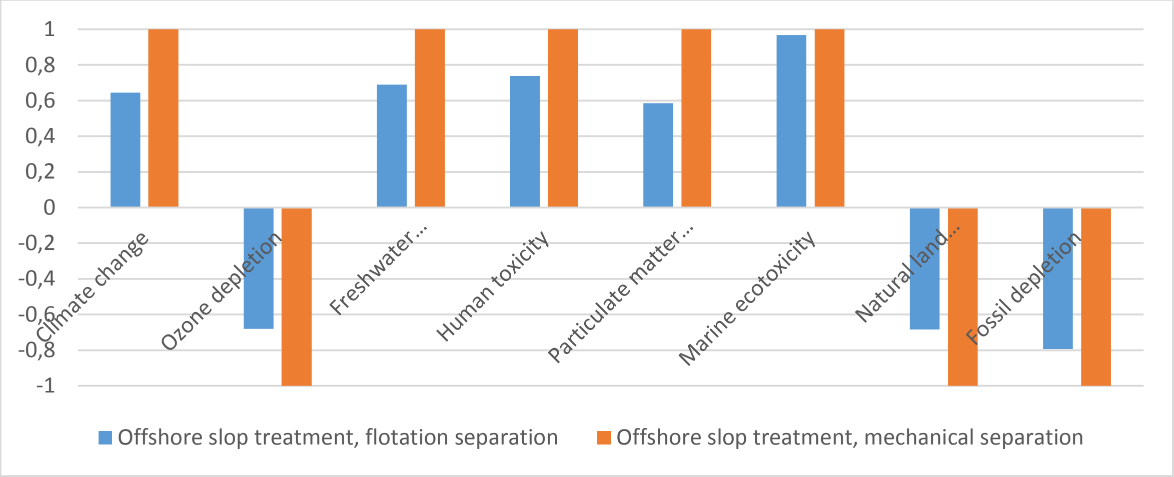


FIGURE 6.10: COMPARISON OF THE TWO OFFSHORE TREATMENT TECHNOLOGIES, SEPARATION AND MECHANICAL SEPARATION

6.4 COMPARITIVE ANALYSIS

In order to classify the environmental performance of the presented scenarios, they are compared in this chapter. Figure 6.11 presents a comparison of the scenarios by using mid-point indicators. Most noticeably in the figure is the clear division of contribution between the offshore scenarios and the other two. Injection and onshore treatment are the most prominent scenarios in the impact comparison, and both the offshore treatment processes are diminutive in comparison, in all impact categories besides marine ecotoxicity. The offshore treatment scenarios are the only ones with negative impacts in several categories.

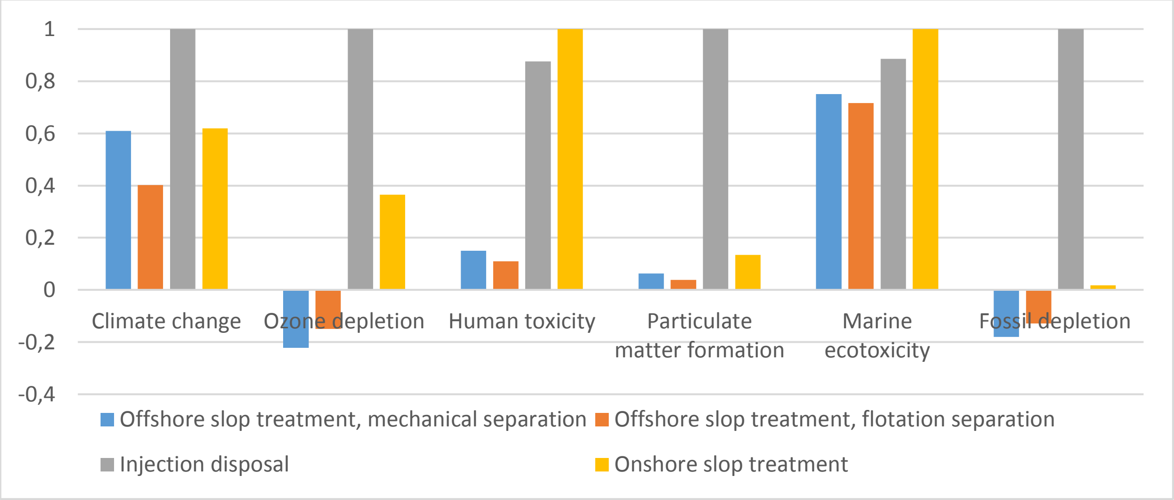


FIGURE 6.11: MID-POINT COMPARISON OF THE THREE SCENARIOS

The onshore treatment scores high in potential for human toxicity and marine ecotoxicity. The many chemicals used in the flocculation process are the main contributors in the human toxicity category. Other contributors on a smaller scale are the cargo transport and the production of electricity. In the climate change category, the incineration of hazardous oil waste is the largest contributor. There is little fossil depletion, and particulate matter formation for the onshore scenario, due to the fact that electricity is the most used energy carrier. In the marine ecotoxicity category, the direct emissions are the primary contributor for all the scenarios.

The injection scenario has the largest impact in the categories fossil depletion, particulate matter and climate change. These impact categories are interlinked and show different perspectives of the same case, the combustion of fossil fuels. Diving deeper into the contributing factors reveals that the operation of the drilling rig is responsible for most of the impacts. The very high impact in the fossil depletion category, relative to the other scenarios, can be explained by the large use of fossil fuels for operating the drilling rig and no reuse of recovery of oil. The oil in the waste is simply lost, eliminating the possibility of further use, but avoiding the need for incineration of oily waste. Burning of diesel for operation of the drilling rig and the production of steel for the well casings are the biggest contributors to the human toxicity for the injection scenario. The process of operating the drilling rig influences the ozone depletion category greatly, with smaller contributions from operating the injection pump.

To summarize the results of the comparison of the scenarios, they are weighted and divided into three impact categories; human health, ecosystems and resources. This is called an end-point impact assessment method, which is identified in chapter 4.2.2 and the results are presented in figure 6.12. In this figure, the resulting impact is stacked on top of each other for each scenario, giving the total impact per scenario. This method of assessing the impacts of the treatment scenarios gives the same impression of the fours scenarios as the mid-point assessment; that the offshore treatments are much lower in impact than onshore treatment and injection, and injection being the most impacting treatment. In addition, the slight difference in impacts of the two offshore scenarios are picked up here as well, as previously discussed in chapter 6.3.2.

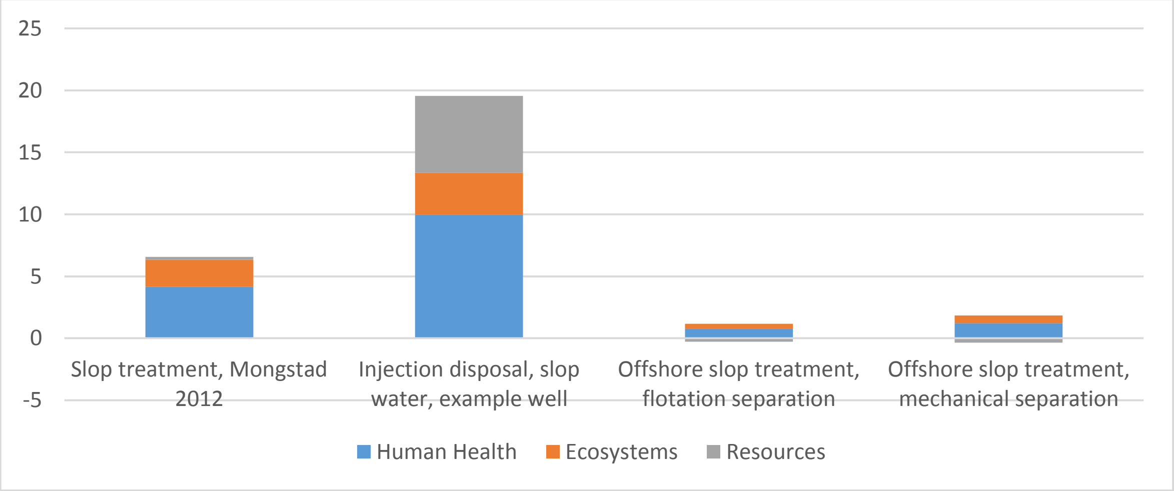


FIGURE 6.12: END POINT IMPACT ASSESSMENT COMPARING THE SCENARIOS

7 SENSITIVITY ANALYSIS

A sensitivity analysis investigates the robustness of the results from the impacts assessment. This is done by altering assumptions made when building the inventory or changing important parameters in the model. The first sensitivity analysis is based on changing the energy carriers used in the different scenarios, the second part concentrates on the choice of drilling fluid used in the injection scenario.

7.1 THE IMPORTANCE OF ENERGY

Energy operates all the different processing stages of the treatment, in all scenarios. This energy comes in many different forms and each scenario is dominated by one specific form of energy. In the injection scenario the offshore vessels are the primary energy consumers and they use diesel, while onshore treatment uses mostly electricity from the grid, and the offshore scenario uses a combination of diesel generators, diesel or heavy oil engines and electricity on land. Where the energy comes from is vital to its environmental impact and is therefore the topic of the first two sensitivity analyses.

7.1.1 THE OFFSHORE SCENARIO, ENERGY CARRIERS

The slop water treatment processes on an offshore rig use diesel generators to supply their energy needs. In this chapter, the implications of switching to alternative energy carriers are explored. The alternatives in question are natural gas turbines and electricity from the mainland. This shift is only applied to the power needs on the rig. Whereas natural gas powered supply boats and cargo ships have been produced in the later years, this is likely a scenario for the future.

According to the Zero foundation, gas turbines are very popular for offshore use, but because of space issues, these turbines only have an efficiency rate of 30-35%, without heat recovery. Which is abysmal compared to the gas power plants onshore with a 60% electric-efficiency. If combined with heat recovery in close proximity to demand for it, the efficiency rate can come up to 80% (Lundberg et al., 2011). This leads to the assumption that the impact results for the gas powered scenario in figure 7.1 and 7.2 is on the conservative side and can be interpreted as using the best available technology. The sensitivity analysis is performed by switching from diesel generators supplying energy to the offshore treatment processes to the Ecoinvent process “Natural gas, burned in turbine/GLO, U”.

The electrification of the NCS has been a matter of political debate this year. The Norwegian government has just recently demanded that Utsirahøgda shall be fully electrified by 2022. This implies that the rigs will no longer be powered with fossil fuels, but with electricity from the mainland through a high voltage direct current cable (HVDC). Not only will this benefit the environmental performance of the offshore slop treatment process, but also have repercussions on a much larger scale. Gas previously burned offshore for energy can now be exported to the European mainland, phasing out more environmentally damaging coal energy.

The installation and production of a HVDC cable is not included in the assessment. This electrification scenario is explored in a sensitivity analysis, where the energy for the offshore treatments is provided by the Ecoinvent process "Electricity, medium voltage {NO}|marked for| Alloc Def, U".

Figure 7.1 and 7.2 shows comparisons of impact results for both offshore treatment scenarios, both mechanical and flotation, when using diesel, natural gas and electricity from the mainland.

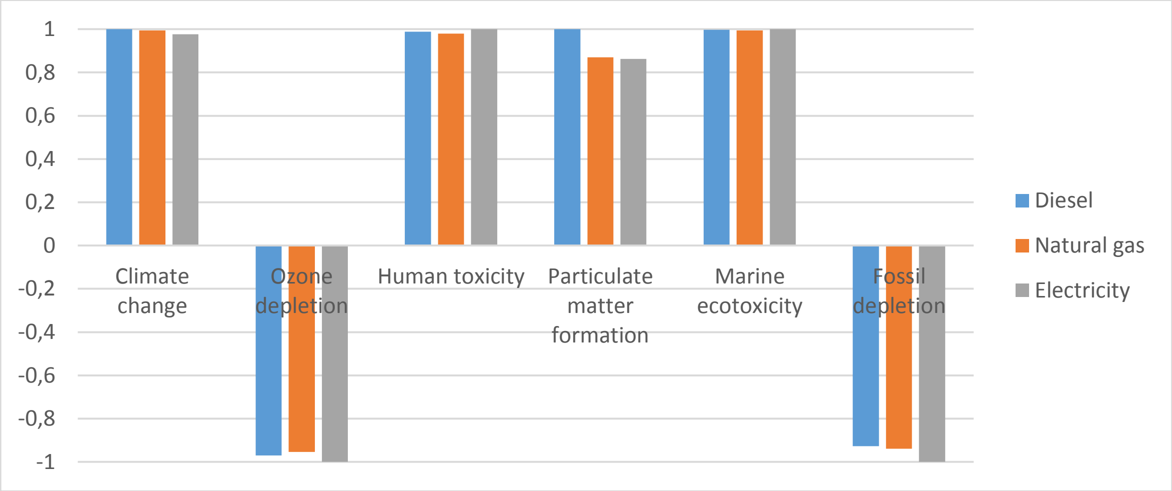


FIGURE 7.1: COMPARISON OF DIFFERENT ENERGY CARRIERS FOR OFFSHORE MECHANICAL TREATMENT SCENARIO

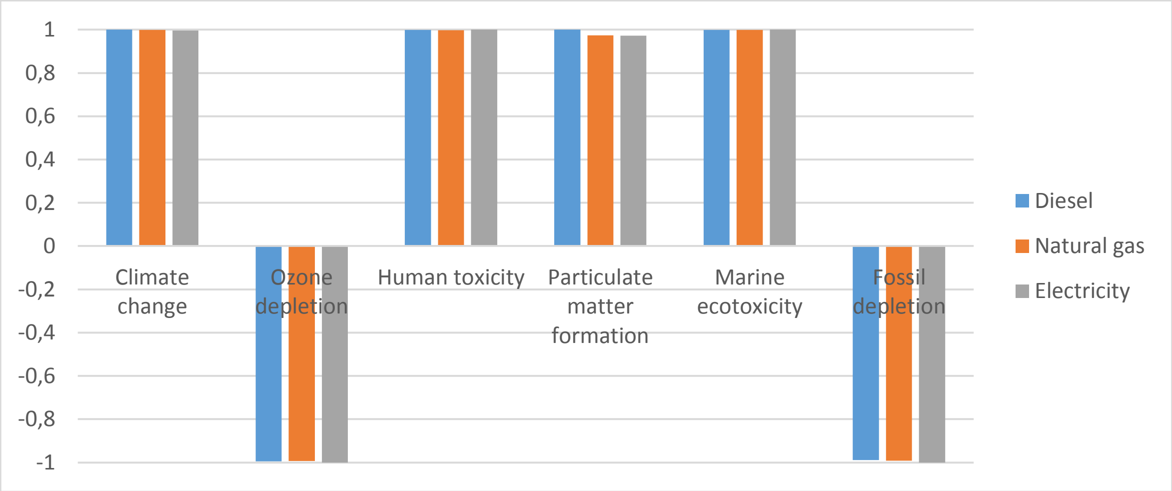


FIGURE 7.2: COMPARISON OF DIFFERENT ENERGY CARRIERS FOR OFFSHORE FLOTATION TREATMENT SCENARIO

The environmental benefits of choosing gas or electricity over diesel are clear from the figures above. In all the impact categories, there is a smaller impact by using gas or electricity rather than diesel. The offshore mechanical separation scenario portrayed in figure 7.1, benefits the most from this energy alteration, because it uses more energy than the flotation treatment. The impact reductions for the flotation scenario are incremental, as illustrated by figure 7.2. The changes in impact is apparent in the particulate matter formation category, fossil depletion and ozone depletion categories. In the ozone depletion category, the negative impact decreases slightly with the use of gas. Burning natural gas releases more NOx than burning diesel, and NOx acts as a catalyst in the ozone depletion cycle. The potential for particulate matter formation experiences the largest change and is decreased by about 15% for both gas and electricity. The offshore treatment scenario already has negative impacts in the fossil depletion category. This development is further benefited by using gas and benefits the most by using electricity.

To summarize the sensitivity results; the model has responded as predicted to the alterations in energy carriers and the electrification of rigs in Norwegian waters will benefit the offshore slop treatment scenario. Still the major impact contributors in this scenario is not affected and this is apparent in the small changes in impact caused by the switch in energy supply on board.

7.1.2 THE ONSHORE SCENARIO, ELECTRICITY MIX

This chapter tests the onshore treatment scenario model for changes in the electricity mix. The facility in the model runs on electricity with a Norwegian mix, since this scenario is based on a treatment facility in Mongstad. Not all slop treatment facilities are in Norway and provided with electricity with a large portion of environmentally friendly, renewable energy. This sensitivity analysis tests what happens with the environmental impacts if the electricity mix is altered. With the Norwegian electricity mix as a reference, Nordic and European electricity mixes are used in the analysis.

The Nordic electricity mix is modelled with the Ecoinvent process “Electricity, low voltage, production NORDEL, at grid/NORDEL U”. Nordel is an association for electricity-cooperation between the Nordic countries. By including the other Nordic countries, the electricity mix includes slightly more coal, oil and biomass than the purely Norwegian electricity mix, which is almost 100% hydropower. The Ecoinvent process “Electricity, low voltage, production RER, at grid/RER U” models the European electricity mix. This electricity mix has about 50% electricity from fossil fuels, strongly influenced by the large use of coal in Germany and Britain. The share of fossil fuels in the European electricity mix is fortunately decreasing with an increasing use of renewable sources such as wind (Eurelectric, 2013).

Figure 7.3 shows a comparison of the results of the sensitivity analysis. The Norwegian electricity mix is the least environmentally harmful, closely followed by the Nordic electricity mix. These two options do not differ that much in electricity mix or environmental impact. The European electricity mix stand out as the option with the largest impacts in all impact categories. This is largely due to the use of coal in electricity production, which includes mining for coal and the large amounts of waste produced from the coal power plants.

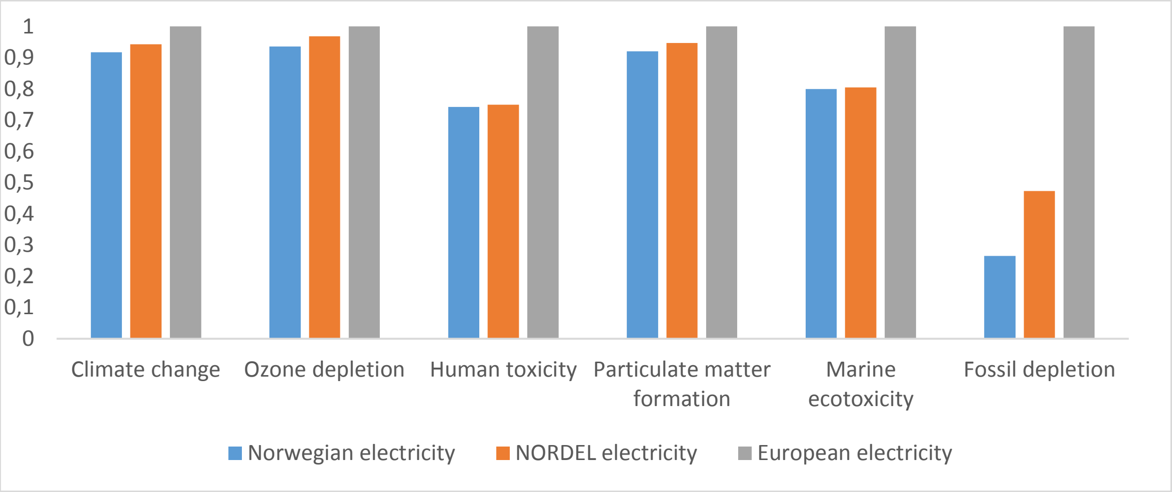


FIGURE 7.3: COMPARISON OF ONSHORE TREATMENT SCENARIOS USING DIFFERENT ELECTRICITY MIXES

In summation, the more renewables there are in the electricity mix, the better for the environment. This is an expected outcome, resulting in the conclusion that the model performs according to plan.

7.2 CHOICE OF DRILLING FLUID

In the injection scenario, the choice of drilling fluid is of great importance to the final impact results, as previously mentioned. The immense variation in not only types of mud, but also the additives and the amounts of them create very different environmental impacts for each drilling fluid. When drilling the injection well only WBM is used. In the original model, a MISA process for the drilling fluid called Gydril was used. In this sensitivity analysis, another drilling fluid, Performadril, is used and the impact assessment results of this are found in figure 7.3.

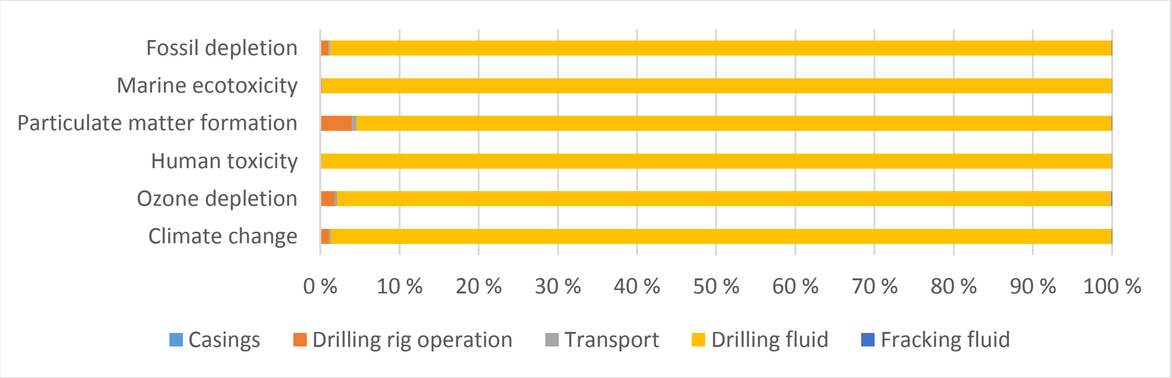


FIGURE 7.4: IMPACTS ASSESSMENT RESULTS FROM SENSITIVITY ANALYSIS, USING PERFORMADRIL DRILLING FLUID

When using Performadril, the drilling fluid process completely engulfs the impact contribution in all impact categories. The operation of the drilling rig is the only other process noticeable in this impact assessment. The main components in the two drilling fluids are the same; barite, potassium chloride and triethylene glycol. The major difference is the concentration of these chemicals. Performadril contains over 180 times as much barite as Gydril, close to 135 times more potassium chloride and a whopping 360 times more triethylene glycol. The doses are the poison in this case, not the chemicals themselves.

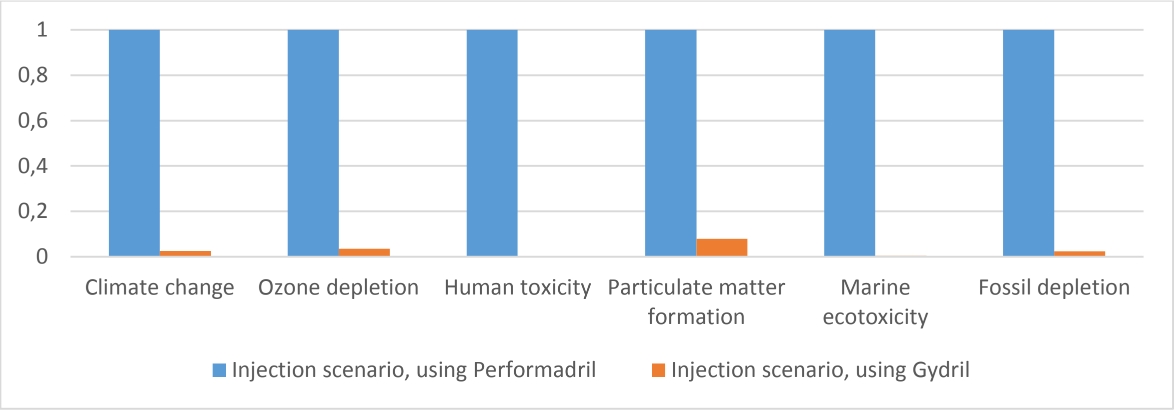


FIGURE 7.5: COMPARISON OF INJECTION SCENARIO USING DIFFERENT DRILLING FLUIDS.

In figure 7.5, the impacts from the two injection scenarios are compared and the message is clear: Using Perfomadril as a drilling fluid is not a good option when only regarding its environmental performance. As always the situation is more complex, and there is a trade-off by using a drilling fluid with lower drilling performance. The drilling fluid affects the drilling capabilities, rate of penetration and can ultimately result in more drilling days. As seen in chapter 6 the operation of the drilling rig is a large contributor in the scenario and a sensitive parameter. More drilling days will also include the increased need for transport logistics.

For the least amount of environmental impact choose a drilling fluid with low concentrations of additives if possible, but the possible repercussions of the prolonged use of the drilling rig must be a part of the discussion, in order to get the best overall environmental performance.

8 DISCUSSION

This chapter evaluates areas of mitigation in accordance with the waste management hierarchy. An evaluation of the results, the uncertainties and limitations of the model and how they affect the final results is also conducted. The results are compared to other studies on wastewater treatment found in the literature to strengthen the model.

8.1 WASTE MANAGEMENT HIERARCHY

To execute an effective waste management strategy, it is prudent to consolidate the waste management hierarchy, which is widely considered the guiding principle in waste management. It shows in order of desirability what to do with the waste and positions the waste management strategies in prioritized order of minimisation, reuse, recycling, recovery and responsible disposal. The greatest benefits are gained by starting at the very source of the waste (Wilson, 1996).

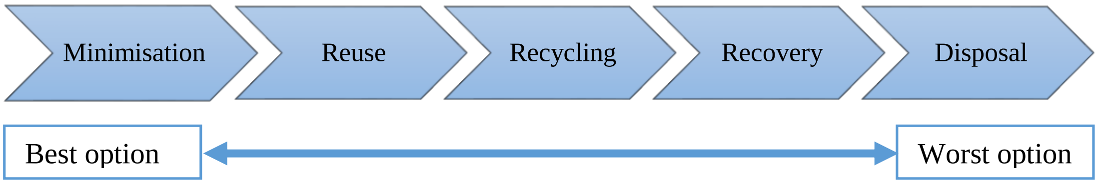


FIGURE 8.1: WASTE MANAGEMENT HIERARCHY, PRIORITIZED STRATEGIES

One thing to take into account when looking at the different scenarios is the aim of the treatment. An offshore treatment facility will typically focus on just getting the water to an acceptable level for discharge and possibly regaining some of the oil for later use. Today most of the pollutant water and slop is injected into wells without prior treatment. Onshore the focus can be more about recycling and reusing because they have the space, the right technology and the economic incentive to do so. Recycled materials can be sold back to the employer or to a different sector all together (Pettersen, 2013).

8.1.1 MINIMISATION

The first and most gainful strategy is minimization. Efforts to minimize the amount of slop includes a review of the number of wells drilled, what type of fluid is used and specific drilling parameters. Slim hole well drilling is a concept where wells are drilled with a much smaller cross section, which can result in faster drilling, decreased consumption of drilling fluids and casings, and decreased volume of waste. The combined reduction of these parameters have a significant impact on slop production as well as other environmental savings connected to drilling (Zhu et al., 1995). However, there is always a trade-off. This strategy involves higher mechanical failures, reduced well-hole length and directional control, which may offset both environmental and economic savings (Pettersen et al., 2013, Kuyken et al., 2003). This technology has not yet gained traction, possibly because of the increasing oil prices over the last years causing the industry not to invest in its further development and improvement. The combination of growing environmental concerns and the increasing cost base of mature field can make this strategy more desirable in the near future (Duhen et al., 1997, Millheim et al., 1995).

Another way of minimizing slop water production is simply good housekeeping and practices concerning deck, tank and pit cleaning. Minimising the likelihood of spills will reduce the volume of water used for cleaning. Using a vacuum cleaner will further reduce the amount of resulting polluted water. Mud saver valves and drip pans are another measure to minimize the volume of slop (Paulsen et al., 2005). These mitigation efforts will reduce the volume of slop water produced, but cleaning is the smallest source of slop water, and efforts placed elsewhere can have a bigger environmental impact on a larger scale.

High performance water based muds with similar properties to OBM have been introduced to the market, but still does not compete with OBM when it comes to drilling in challenging environments such as in high temperature, high pressure wells, and wells with a high incline (Svensen and Taugbol, 2011). Drilling with OBM gives better drilling performance than the other drilling fluids, but it also generates the largest volumes of waste. It is desirable to shift towards more WBM use because of environmental concerns and less transportation needs. These environmental savings must be compared to an eventual increase in drilling rig days and efforts. A paradox presented by Paulsen et al. argues against this logic: Using a fluid with low costs allows for an attitude towards overuse and wasting of the drilling fluid, as opposed to an expensive fluid system, which can promote efficient recovery systems (Paulsen et al., 2006).

8.1.2 REUSE

Reusing is performed during the cleaning of tanks and boats, where the washing water is used several times before sent to slop waste handling. The rate of reuse is dependant of the solids content. If the solids can be separated from the water, the reuse can continue. The design of tanks and the washing method are factors of consequences for the volume of slop water produced. Cylindrical tanks and lack of internal components makes it easier to clean tanks and less water is needed. Manual cleaning generates less washing water than automatic washing, but takes longer time and raises the risk of confined space incidents. Using an automatic washer also gives a higher rate of reuse possible and can reduce the amount of produced washing water by 70% (Massam et al., 2013, M-I Swaco).

Reusing drilling fluid is another waste handling strategy. In 1999 Statoil took a more holistic approach to the purchasing agreements with drilling fluid suppliers. From a commodity perspective with emphasis on the individual chemicals used in the fluid, to new contracts focusing more on the technical specifications of the fluid. The suppliers were obligated to buy the used slop back, if it was still within specification limits. This is called extended producer responsibility and is to ensure and promote resource efficiency (Paulsen et al., 2006). The result of this alteration in supplier contracts was a reduction of drilling fluid costs for Statoil. Now, there existed an incentive to reduce, reuse and conserve the drilling fluid, which was lacking in the old agreements (Svensen and Taugbol, 2011, Paulsen et al., 2006). The reuse factor in OBM is now at approximately 70%, but it will never reach 100 % because of losses down the well, in cuttings and through seepage. The trend of reusing fluid also applies to the WBMs, although at a lower level since they are less resistant to contamination (Svensen and Taugbol, 2011). The reuse of drilling fluid has ramifications also in the transportation to site as well as the slop transportation. Since there will be used less fluid, less will reach the platform and transportation volume has been reduced, saving the environment from the pollution of transport by boats and the potential risk of spills (Paulsen et al., 2002).

8.1.3 RECYCLE

Through the TCC process, oil from the slop is recycled and can be used again as heating oil. This process is highly beneficial for the environment, as the impact assessment in chapter 6 showed. One option for increasing the amounts of oil recycled is to treat the decanter residue, which is oil with a high solids content and some water, instead of sending it to incineration. This will need additional energy input to both the decanter and the TCC, but will quite possibly be a better option than the incineration, which is very harmful process in the system. Achieving a higher recycling rate of the oil is desirable from an environmental perspective as long as the benefits of it exceeds the impact of the added input needed.

The industry is eager to find alternative uses for the wastes from drilling operations. When looking at the bigger picture, both financially and environmentally, the disposal of hazardous waste is a serious matter. An interesting aspect of the ongoing research is to turn the waste into a resource through different end-uses of it. Dried sludge and the low-grade oil decanter residue from onshore slop treatment can be ingredients in asphalt, substituting fine sand and bitumen (D’Andrea et al., 2014, Goedkoop et al., 2009, Getliff et al., 2000). The dried sludge is not a parameter of great importance to the environmental impact of any of the systems. If the incineration of the oily waste could be circumvented, it would benefit the environment greatly and further solidify the difference between the injection scenario and the other treatments.

8.1.4 RECOVERY

In the waste management hierarchy, recovery stands for energy recovery and is the second least favourable option. During incineration the oily hazardous waste, heat can be recovered and used as an energy carrier. This can be performed by either adding waste-heat recovery systems to the incinerators or feeding the waste into an existing boiler. In the model, the hazardous waste incineration is without any kind of recovery, and is one of the reasons for the high impact it has on the climate change category, seen in the results presented in chapter 6.2 and 6.3.

8.1.5 DISPOSAL

Disposal is the last option and should only be used when all other options are exhausted. This is because it is the end of the road for the waste, and the material or inert energy in the waste cannot be exploited. The disposal must be in the most environmentally friendly manner possible, under the given circumstances of the waste and the available technologies.

8.2 COMPARISON WITH STUDIES FOUND IN LITERATURE

Published LCA studies of the treatment of slop water are non-existent so there are little grounds for direct comparison of impact results. Produced water has gained more attention, but the focus of the literature is how to mitigate the volume stream and the most economical way of handling it and the processes involved in the treatment in order to meet the emission regulations (Al-Ani, 2012, Dixit and Patel, 2010, Eia and Hernandez, 2006, Knudsen et al., 2004, Mueller et al., 2013, Mat et al., 2006, Puszkarewicz, 2008, Thamer et al., 2007). There are however multiple LCA studies on the environmental impact of the treatment of municipal wastewater. Comparing their result with the results from this study will give an inkling of the validity of the work.

Studies of sewage sludge treatment involve processes of thickening, dewatering, stabilization and either landfilling, agricultural land application or incineration. In a LCA study of sewage sludge treatment in Japan it was concluded that landfill, digestion, drying and incineration all have a high contribution to climate change potential. This resonates with the findings in this study, namely the part of incineration and landfilling, even though some of the processing is different for the sewage sludge (Hong et al., 2008). In another study of sewage waste and food waste, the difference in decentralized and centralized treatment approaches were analysed. The results showed that transportation represents a main source of impact throughout the categories (S.D. Pillay, 2002). Parallel lines from this can be drawn to the importance of transportation in this study, that it is a parameter of great importance to the environmental performance.

Also in the sewage treatment industry there is a recognition of the opportunity to get a reusable product out of the treatment process, «productification» (Suh et al., 2002). This mirrors the oil recovery in the slop sludge treatment.

Two studies in particular in this study have been a source for the model inventory, James et al and Saasen et al. The latter study compares CO2 and NOx emissions from injection and from transportation and handling onshore. He concludes with the injection being the larger emitter of the two and the drilling rig is responsible for most of it. This is exactly the same conclusions that can be drawn from this study. James et al when comparing the energy of injection and onshore handling comes to the opposite conclusion. He states that injection consumes 48% less energy than processing onshore. This is because he only considered the operation phase of both these scenarios. As mentioned before in this thesis, the operation of the slop injection has the lowest environmental impact, but this is not the whole treatment process. The difference in these two studies illustrate the importance of including the whole life cycle of a product to make the right decisions. One can argue that since these studies are sources for parts of the inventory, that it is not surprising that we get the same results, but my model is much more comprehensive and looks at different comparisons criteria, and still we come to the same conclusion. This consensus leads to giving the results and conclusions of this thesis validity.

8.3 DATA QUALITY AND UNCERTAINTY

The quality of the impact assessment results are a product of the data applied in the inventory. There are several sources of uncertainty present in an LCA study. One example is the quality of the processes used in the study. They might be inaccurate or outdated because of advancements in technology. Assumptions made in the model is another source of uncertainties. There are simplifications made and shortcuts taken, to make up for the impossibility of gathering information about all the processes connected to a products life cycle. Yet another example of uncertainties featured are the characterization models who calculate the impact. There are categories such as climate change and human toxicity, which are not fully understood and therefore incomplete. In the ReCiPe method, there are three different perspectives with different uncertainties and decisions on system boundaries. In this thesis the hierarchical perspective was used, based on general consensus regarding policy making and time frame.

In this study the aim was to create general models of different ways of treating slop water. It is a challenge to make a general model in LCA, because this generalization leads to uncertainties. Because the models are an average of a spectrum, it may not be a correct representation of all treatments practised. As mentioned many times before in this thesis, the slop itself varies and there is not only one way of treating it. A selection of the most popular treatment methods have been chosen for the study to get the general model possible. The slop content and level of pollution chosen for this thesis is also a generalization.

In this thesis, the data for the inventory is based on several different sources, as described in chapter 5.1. Even though a thorough investigation of the system boundaries and assumptions made for the data collected has been made, there may still be some discrepancies between the sources that have not been accounted for. This can be a source of error, but will not have a substantial effect on the final results.

The direct emissions from offshore treatment are based on the assumption that they are similar to the onshore scenario. The onshore emissions are from actual treatment facilities and therefore assumed reasonable. The model will benefit from using actual emissions to sea from the treatment offshore. The emissions may be larger offshore because the slop treatment is not as extensive. On the other hand, many of the heavy metals and other pollutants are found in the oily phase of the slop water and, this is separated out with the treatment received offshore, and the oil emissions offshore are comparative to the onshore oil emissions. In other words it is an area with uncertainties.

The chemicals used in the onshore scenario are collected from the operation of the Mongstad facility, and are deemed reasonable. The available information on the chemicals used in the offshore treatment was however minimal and sourced from literature about oily wastewater treatment. The onshore scenario uses many more chemicals than the equivalent offshore processes. This may be a representation of reality because the offshore treatment is more simple and has space limitations for storing said chemicals, or this is a sign of missing chemicals not included in the offshore model because of lack of information.

The energy use in the processes is a deciding factor of its environmental performance, as the impact analysis in chapter 6 shows. One process in particular has such a high energy use that it determines the performance of the whole scenario it is a part of, namely the operation of the drilling rig in the injection scenario. Since this is parameter so decisive, it is important that it is reasonable. The type of rig chosen is a semisubmersible because such rigs are common on the NCS. The rig is assumed to be unanchored and have dynamic positioning because of the relatively short drilling time. These choices have a large impact on the energy use of the operation and leads to an energy consumption on the upper scale, compared with the other rig options available. The operation of the rig is given in days as the functional unit, and the number of days is taken from Saasen’s article on comparing CO2 and NOx emissions in injection and onshore treatment of slop. Investigating well specifics found in the fact pages of NOAG, the number of days chosen for the example well in this study is a conservative estimate compared to the majority of wells on the NCS. The sources for this information are reliable and the process of drilling an injection rig is feasible.

The energy use of the different treatment technologies is based on the average of several different sources, and are therefore found to be within reason, but with the uncertainty that follows using average values. These parameters do not influence the results in a critical manner anyhow.

The transportation in all its forms is important to the performance of all the scenarios. The distances travelled are based upon combined averages for operating in the North Sea. This can lead to the model not being applicable for other areas such as the Barents Sea or Lofoten. The specific vessels chosen for transport is a source in uncertainty. In lack of specifics about the vessels used for transportation assumptions have been made, and may not reflect the transportation in reality.

8.4 LIMITATIONS OF THE STUDY

A LCA study provides plentiful information about the environmental performance of a system, but there are several aspects to a system that are not picked up by the environmental issues that are specified in the goal and scope of a study. Associated risks and socio economic perspectives are examples of this. The limitations of this particular study are presented here

As mentioned in chapter 3, in the description of the injection scenario, in 2010 several injection wells started leaking. This discovery lead injecting of slop to an abrupt halt, and the method of injection was reconsidered. Today, the use of injection is increasing again with deeper wells being drilled to avoid leakage. Since re-entry has happened before, a risk premium should be added to the evaluation of the injection scenario, interpreting the results as below the actual posed risk and impact for the environment. Including this risk as a potential impact, gives the injection scenario an even worse environmental performance, and does not alter the scenario ranking.

Political and economic hurdles are not included in the results of this study and the recommendations for the development of slop treatment may not be accomplishable because of them. Raising the CO2 tax would catalyst the use of cleaner energy, and the electrification of Utsirahøgda might be an economic incentive and therefore carried out faster. When discussing installation of slop treatment units on drilling rigs, it is important to include the whole life cycle costs of the investments when comparing them to the injection scenario. This may lead to less drilling of new injection wells and more offshore treatment units, which is the best for the environment, as concluded in this study.

9 CONCLUSION

The aim of this study was to conclude a comparative LCA study of different ways of treating slop water. The results of this analysis shows that offshore treatment is the most environmentally beneficial treatment of slop. Injection is the scenario with the highest environmental impact, because of the process of drilling an injection well. The onshore treatment is the scenario with the intermediate environmental performance.

The practice of injection is picking up speed again after a ceasing of such activities due to leakage in 2010. This may not be the most favourable development, seen from an environmental perspective, also considering the risk of leakage happening again. Only about 40% of the drilling rigs on the NCS today has slop treatment units installed, and drawing from the results of this thesis, this number should be increased.

The results from the impact assessment displays the importance of the drilling of an injection well and how important it is to include all aspects of the life cycle of a treatment, to get the whole picture. The operation of the injection treatment is the least environmentally damaging of the scenarios. In the event of repurposing an exhausted oil production well to inject slop, this scenario would be the least harmful to the environment.

Onshore treatment is the option with the middle environmental performance. The most influential processes within this scenario are the transportation, flocculation and TCC. The disposal of hazardous waste is very influential in the climate change category because of the incinerations release of GHGs. The flocculation is a large contributor due to all the chemicals added, whereas the TCC’s impact comes from its considerable energy use.

Offshore treatment has the best environmental performance, and using the flotation technology is slightly better than the mechanical separation. Transport and the onshore TCC unit are the main impact contributors in this scenario, but in a smaller scale than in the onshore scenario because of volume reductions by the offshore treatment.

The sensitivity analysis showed the imperative importance of the choice of drilling fluid. WBM is preferred over OBM and with as low a concentration of additives as possible. The future scenario of electrification of rig on the NCS will further benefit the environmental performance of the offshore slop treatment scenario.

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11 APPENDIX

A: DRILLING MUD PROPERTIES

Drilling mud is a mixture of bentonite clay, drilling weight material usually barite ($BaSO_4$), or ilmenite, organic polymers, emulsifiers, salts and other chemicals suspended in a liquid. The weighting agents embodies up to 90% of the mud and is used to regulate hydrostatic pressure in the well. It contains heavy metals as impurities and is together with clay the main source of heavy metals in the drilling discharges. Salts such as sodium or calcium chlorides establish conditions for isotonic osmotic pressure between the water in the emulsion and the surrounding formation water. The clay and polymers ensure the fluid viscosity needed. In addition to this are oxygen scavengers pumped into the well to prevent corrosion damage to the equipment. Lime is also added to reduce corrosion and stabilize emulsions in the mud, by increasing the pH (Patin, 1999). A careful selection of different additives are added to the drilling fluid base according to which properties are desired. Density, flow properties, filtration properties, alkalinity and lubricity are some of the factors of performance altered by using additives. Every well is different and therefore the drilling fluid is customized to each well (Darley et al., 1988).

Drilling muds are used as an aid in drilling by:

- Removing the cuttings from the wellbore and moving it to the surface, with as little disintegration as possible.
- Cooling and lubricating the drill bit, preventing damage to the equipment
- Increases pressure in the wellbore to prevent the well from caving in
- Sealing permeable formations during drilling
- Transmitting hydraulic energy to the drill bit
- Maintaining stability in the wellbore

B: BASIC MATHEMATICS

Both the nomenclature and the model formulation presented is based on the work of Nobel laureate Wassily Leontief. The open Leontief model describes the interdependence makes up the basis of LCA, and is nearly always assumed linear.

TABLE 11.1: NOMENCLATURE USED FOR THE VECTORS AND MATRICES USED IN THE MATHEMATICS OF LCA (STRØMMAN, 2010)

Sets	**Pro** **Str** **Imp**	**Processes** **Stressors** **Impacts**	
Matrices and variables	A	*pro x pro*	Matrix of inter process requirements
	y	*pro x 1*	Vector of external demand of processes
	x	*pro x 1*	Vector of outputs for a given final demand
	L	*pro x pro*	Leontief inverse, matrix of outputs per unit of external demand
	S	*str x pro*	Matrix of stressor intensities per unit output
	e	*str x 1*	Vector of stressors generated for a given external demand
	E	*str x pro*	Matrix of stressors generated from each process for a given external demand
	C	*imp x str*	Characterization matrix
	d	*imp x 1*	Vector of impacts generated for a given external demand
	D_{pro}	*imp x pro*	Matrix of impacts generated from each process for a given external demand
	Dstr	*imp x str*	Matrix of impacts generated from each stressor for a given external demand

The A-matrix contains the inputs to production from each process, the so-called cooking recipe. In the columns of the matrix we find the required input to produce one unit of output for the respective process, for a given demand y. The output required from the different processes, given an external demand y, is found in the x-vector. On the basis of these statements we can deduct the material balance, a crucial equation in LCA and input output.

$Ax + y = x$

Rearranging this equation gives us

$x = (I - A)^{-1}y$

The Leontief inverse matrix, denoted by L, is defined by

$L = (I - A)^{-1}$

Combining the two expressions above yields

$x = Ly$

Showing us that the Leontief inverse represents output per unit of external demand. All these expressions together constitutes the open Leontief model.

Calculating the emissions, or as they are called in LCA stressors, associated with an external demand we need to incorporate the S matrix. This stressor intensity matrix gives us values for the stressor intensity per unit output. The stressors generated from a given external demand is represented by the e vector and can be calculated from the equation below.

$e = Sx$

This vector is an aggregation of the stressors from each process. To get a more detailed version of the stressors generated, and to se how much the various processes contribute to the total stressor load the x vector is diagonalized (hat ^operator).

$E = S\hat{x}$

To convert the different emissions to comparable equivalents we use the characterization matrix, C. for instance, global warming potential is measured in CO2 equivalents, so all the emitted greenhouse gasses needs to be converted into this equivalent through the characterization matrix. The other impact categories and their respective measurement units are presented in table 3.2. The d vector shows total impacts for a given external demand and can be calculated from the equation below

$d = Ce$

To show the impacts per process or per stressor in a matrix, Dpro and Dstr are calculated from the equations under. The sum of the rows in each of these matrices is equivalent to the vector of total impact, d.

$D_{pro} = CE \quad D_{str} = C\hat{e}$

Calculating the stressors and the impact from a given demand is called contribution analysis and can be followed by a structural path analysis. This type of analysis tracks pathways from the demand in a foreground process through the network of production to identify key background processes that has a significant contribution to the total impact.

C 1: INVENTORY FOR THE INJECTION SCENARIO

The functional unit is 1m^3, but one well holds 43 573 m^3 f slop.

Drilling of well	amount	unit	Process	Documentation
Semisubmersible rig	25	days	Drilling rig, drilling operations, dynamic positioning	Saasen et al. 2014
Drilling mud	450	m^3	Glydril WBM (1.25 sg)	Based on Saasen et al., 400m^3 drilling fluid discharge.
Well bore casings	30	m	Construction 36" section casing (30")	Estimate of generic topsection.
	570	m	Construction 16" section casing (13 3/8")	Saasen et al. 2014
	412	m	Construction 13 5/8" section casing (13 5/8")	Saasen et al. 2014
supply/transport	323,8	hr	Far Serenade, at economy speed (11.3 kn)	Logistics from Saasen et al. Distance is avarage travelling distance from Halliburtons records, to and from. Speed provided by process description.
	33	hr	Transport, helicopter {GLO}|market for| Alloc Def, U	Logistics from Saasen et al. Distance is avarage travelling distance from Halliburtons records, to and from. Speed is an average curising speed from Bell helicopters.
Fracking fluid	42000	kg	Carboxymethyl cellulode, powder {GLO}|market for| Alloc Def, U	Substitutuion for hydroxyethyl cellulose, amount from (AEA, 2012).

operation of injection pump	amount	unit	Process	Documentation
Hihg pressure HT 400 Injection pump	142	kWh/m^3	Electricity	NOGA and James et al 2002 report this pump for offshore injection.

End of life , plug & abandonement	amount	unit	Process	Documentation
P&A	10	days	Drilling rig, drilling operations, dynamic positioning	Saasen et al 2014
	14	hr	Transport, helicopter {GLO}|market for| Alloc Def, U	Logistics from Saasen et al. Distance is avarage travelling distance from Halliburtons records, to and from. Speed is an average curising speed from Bell helicopters.
	81,6	hr	Far Serenade, at economy speed (11.3 kn)	Logistics from Saasen et al. Distance is avarage travelling distance from Halliburtons records, to and from. Speed provided by process description.
Cement plug	7680,6	kg	Cement,Portland {CH}|production|Alloc Def,U	Cement plug length provided by OISD,2013.

C 2: INVENTORY FOR THE ONSHORE TREATMENT SCENARIO

Operation of Halliburton slop treatment facility, Mongstad, 1m^3

Slop treatment, onshore.	amount	unit	Process	Documentation
Flocculation and flotation	0,33	kWh/m^3	Electricity, low voltage, production NO, at grid/NO U	Based on MISA Process, «Water treatment, dissolved air flotation, onshore» (MISAtest39325500402.
	0,099	kg	Sodium Hydroxide 30%	Own dilution mix from security data sheet provided by Halliburton (se own inventory)
	0,032	kg	UNIFLOC AE 300	Own mix from security data sheet provided by Halliburton (se own inventory)

	0,099	kg	Hydrochloric acid, without water, in 30% solution state {RER}|hydrochloric acid production from the reaction of hydrogen with clorine| All Def, U	Amount provided by Halliburton, chosen production process is the most popular one.
	14,55	kg	Iron (III) chlorine, 40% in H2O, at plant/CH U	Provided by Halliburton
	0,049	kg	Benzal chloride {GLO}|market for| Alloc Def, U	Substitue for BAC 50, provided by Halliburton.
	656,9	kg	Tap water, at user/RER U	Estimated from total water use, divided by mass through process, provided by Halliburton.
Biological treatment	2,12	kWh/ m^3	Electricity, low voltage, production NO, at grid/NO U	Energy use estimated from the use of 10 compressors and the total energy use provided by Halliburton
	1,91	kg/m^3	Flex Bio 10-7	Own mix from security data sheet provided by Halliburton (se own inventory)
	0,15	kg/m^3	STRUKTOL SB 2080	Own mix from security data sheet provided by Halliburton (se own inventory)
Decanter	3	kWh/ m^3	Electricity, low voltage, production NO, at grid/NO U	Based on Roger Kahlil 2007, stating 1-2 kWh/m^3 for decanters, tricansters energy use are higher.
	0,0002	kg	Polyacrylamide, at production	Provided by Halliburton, substitute for Nalco, ULTIMER 7752
	194,96	kg	Tap water, at user/RER U	Estimated from total water use, divided by mass through process, provided by Halliburton.
TCC	233	kWh/ m^3	Electricity, low voltage, production NO, at grid/NO U	Estimated from Termtech product specifications.
	3,68	kg	Diesel, at regional storage/RER U	Estimated from interviewing operators of TCC unit, at Mongstad.

Output	0,018	kg	Light fuel oil, at refinery/RER U	Provided by Halliburtons
Direct emissions, subcompartment: ocean	3,62E-05	kg	Arsenic	All direct emissions are the average over two years of operation at Mongstad treatment facility and SAR’s Facility in Tananger. Provided by Norskeutslipp.no
	4,44E-03	kg	Barium	
	2,24E-05	kg	Cadmium	
	1,43E-05	kg	Chromium	
	1,84E-06	kg	Copper	
	6,73E-05	kg	Mercury	
	8,87E-05	kg	Molybdenum	
	3,53E-04	kg	Nickel	
	6,76E-04	kg	Oils, biogenic	
	9,04E-03	kg	Lead	
	1,87E-04	kg	Tin	
	3,03E-05	kg	TOC	
	1,60E+00	kg	Vanadium	
	2,66E-05	kg	Zinc	
Transport	551,5	tkm	Cargoship, average NO, travelling	Distance is the avarage travelling distance from Halliburtons records, to and from.
	329,3	tkm	Operation, offshore supply vessel	Distance is the avarage travelling distance from Halliburtons records, to and from.
	17,2	tkm	Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}|market for| Alloc Def, U	Distance to the nearest landfill and hazardous waste treatment site.
Infra-structure	2,05E-07	p	Wastewater treatment facility, capacity 1,6E8l/year {CH}| construction | Alloc Def, U	Waste water treatment class 5, based upon the description in Ecoinvent manual.
Disposal	108,2	kg	Disposal, inert waste, 5% water, to inert material landfill	Substitute for dried sludge from TCC unit. Amount provided by Halliburton

	2,57	kg	Disposal, used mineral oil, 10% water, to hazardous incineration/CH U	Substitute for the low-grade oil from decanter. Amount provided by Haalliburton.

Chemicals used in treatment process,

Documentation from data security sheets provided by Halliburton.

Chemical	amount	unit	Process
Flex Bio 10-7 [1 kg]	0,2	kg	Phosphoric acid, industrial grade, without water, in 85% solution state {RER}| purification of wet-process phosphoric acid
	0,03	kg	Sulfuric acif {RER}| production| Alloc Def, U
	0,775	kg	Tap water, at user/RER U
	4,00E-10	p	Chemical factory, organics {RER}|construction| Alloc Def, U
Sodium Hydroxide 30% [1kg]	0,6	kg	Sodium hydroxide, 50% in h2o, producion mix, at plant/RER U
	0,4	kg	Tap water, at user/RER U
UNIFLOC AE 300 [1kg]	0,225	kg	Kerosene, at refinery/RER U
	0,04	kg	Ethoxylated alcohol, unspecified, at plant/RER U
	0,66	kg	Tap water, at user/RER U
	4,00E-10	p	Chemical factory, organics {RER}|construction| Alloc Def, U
STRUKTOL SB 2080	0,8	kg	Fatty alcohol {GLO}|market for| Alloc Def, U
	0,2	kg	Fatty acid {GLO}|market for| Alloc Def, U

C 3: INVENTORY FOR OFFSHORE TREATMENT SCENARIO

Mechanical separation offshore, 1m^3

Decanter	**amount**	**unit**	**Ecoinvent process**	**Documentation**
Decanter feed pump	0,08	kWh/m^3	Diesel, burned diesel-electric generating set/GLO U	Assumption: one mono feed pump with 0.75 kW capacity, operated 6 h/day to pump 60m^3 slop pr day.
Decanter separation	2	kWh/m^3	Diesel, burned diesel-electric generating set/GLO U	Estimated from a decanter with 30kW capacity. Only 20kW is assumed to needed for treating 60m^3 a day for 6 h/day.
Centrifuge	**amount**	**unit**	**Ecoinvent process**	**Documentation**
Disc stack feed pump	0,08	kWh/m^3	Diesel, burned diesel-electric generating set/GLO U	Assumption: one mono feed pump with 0.75 kW capacity operated 6 hrs/day to pump 60m^3 slop pr day.
Disc stack separation and heating	0,6	kWh/m^3	Diesel, burned diesel-electric generating set/GLO U	Based on a separator with 5kW capacity. Assuming the separator treats 40m^3/day (volume reduced from the decanter), operated for 6 hrs/day and that only 4kW is absorbed.
Filter	**amount**	**unit**	**Ecoinvent process**	**Documentation**
filtration media	0,25	kg/m^3	Polypropylene, granulate at plant/RER/U	Product specification from filter manufacturer states that a cartridge of 0,5kg with 90% propylene, can remove 2 kg hydrocarbons (Twinfilter).

Flotation separation offshore, 1m^3

Flocculation	amount	unit	Ecoinvent process	Documentation
Slop water feed	0,08	kWh/m^3	Diesel, burned diesel-electric generating set/GLO U	Assumption: one mono feed pump with 0.75 kW capacity, operated 6 h/day to pump 60m^3 slop pr day.
Emulsion breaking	0,05	kg/m^3	Acrylic acid, at plant/RER U	Based on (Mat et al., 2006)
Coagulation and flocculation	0,12	kg/m^3	Aluminium sulphate powder, at plant/RER U.	Based on dosage used in (Puszkarewicz, 2008). (Eckenfelder, 1989) stated 0,07-0.25 kg/m^3. (Thamer et al., 2007) reported 0,025-0,07 kg/m^3. (Sharaai et al., 2009) reported 0,13 kg/m3.
	0,005	kg/m^3	Bentonite at processing/DE U.	Based on (Armenante), (Puszkarewicz, 2008), using 0,8 kg/m^3 powdery diatomite.
	0,03	kg/m^3	Sodium Hydroxide, 50% in H$_2$O, production mix, at plant/RER U.	Based on (TAUD, 2003): 0,03 kg/m^3. (Thamer et al., 2007): 0,007-0,03 kg/m^3 for lime. (Al-Ani, 2012): 0,03 kg/m^3.
Dosing pump	0,04	kWh/m^3	Diesel, burned diesel-electric generating set/GLO U	Assuming two 0,19 kW pumps, in operation for 2 h/day. Stirring not considered
DAF	**amount**	**unit**	**Ecoinvent process**	**Documentation**
Dissolved Air Flotation	0,207	kWh/m^3	Diesel, burned diesel-electric generating set/GLO U	Based on (Johnson et al., 2009): 0,05-0,075 kWh/m^3. MISA library, «Water treatment, dissolved air flotation, onshore» (MISAtest39325500402): 0.33kWh/m^3. (Vlasopoulos et al., 2006): 0,221kWh/m^3. Average between all these values in 0.207 kWh/m^3

Filter	amount	unit	Ecoinvent process	Documentation
Filtration media	0,25	kg/m^3	Polypropylene, granulate at plant/RER/U	Product specification from filter manufacturer (Twinfilter) states that a cartridge of 0,5kg with 90% propylene, can remove 2 kg hydrocarbons.

Transport of sludge to onshore facility, per m3

Transport	amount	unit	Ecoinvent process	Documentation
Cranes	7,5	kWh/m^3	Diesel, burned diesel-electric generating set/GLO U	(James and Rørvik, 2002)
	7,5	kWh/m^3	Ecectricity, land	(R.W. James, 2002)
Cargo vessel	551,5	tkm	Cargoship, average NO, travelling	Average travelled distance, based of logistics provided by Halliburton.
Supply vessel	329,3	tkm	Operation, offshore supply vessel	Average travelled distance, based of logistics provided by Halliburton.

Onshore final treatment and disposal, pr m^3

Onshore sludge treatment	amount	unit	Ecoinvent process	Documentation
Decanter	2,86E-04	kg/m^3	Polyacrylamide	Provided by Halliburton, substitute for Nalco, ULTIMER 7752
	275,4	kg/m^3	tap water, at user, RER U	Estimated from total water use, divided by mass through process, provided by Halliburton.
	2,33	kWh/m^3	Electricity, low voltage, production NO, at grid/NO U	Based on Roger Kahlil 2007, stating 1-2 kWh/m^3 for decanters, tricansters energy use are higher.
TCC	543,4	kWh/m^3	Electricity, low voltage, production NO, at grid/NO U	Estimated from Termtech product specifications.
	20,4	kg/m^3	Diesel, at regional storage/RER U	Estimated from interviewing operators of TCC unit, at Mongstad.

Output	98,4	kg/m^3	Light fuel oil, at refinery/RER U	Provided by Halliburton
Disposal	2,57	kg/m^3	Disposal, used mineral oil, 10% water, to hazardous incineration/CH U	Substitute for the low-grade oil from decanter. Amount provided by Halliburton.
	108,2	kg/m^3	Disposal, inert waste, 5% water, to inert material landfill	Substitute for dried sludge from TCC unit. Amount provided by Halliburton
Transport to disposal	17,2	tkm	Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}|market for| Alloc Def, U	Distance to the nearest landfill and hazardous waste treatment site.

D: COMPARISON OF CHEMICALS USED IN FLOCCULATION