NTNU – Trondheim
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Life Cycle Assessment of Slop Water Management in Challenging Offshore Drilling Operations

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Master in Industrial Ecology
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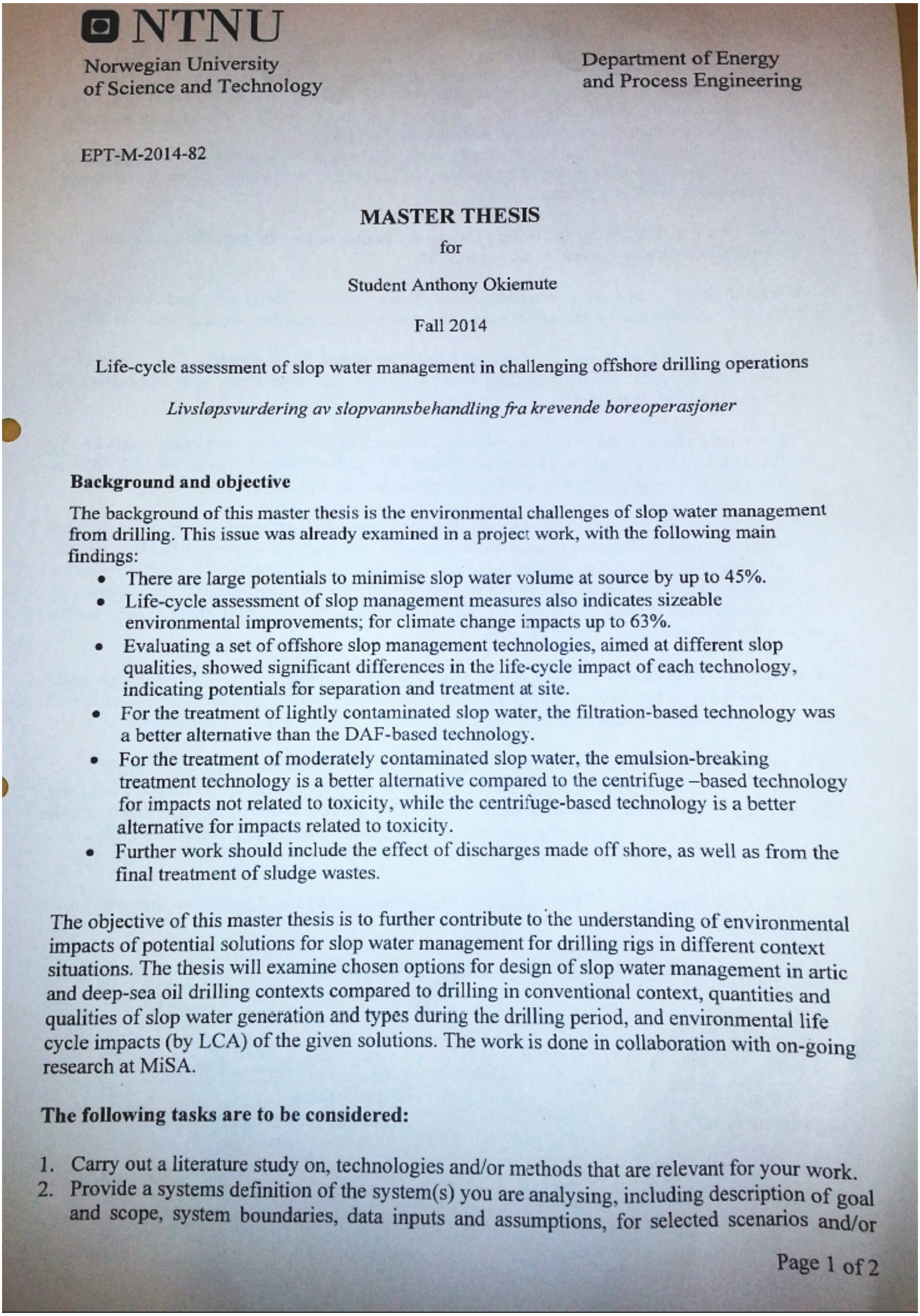

NTNU

Norwegian University
of Science and Technology

Department of Energy
and Process Engineering

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MASTER THESIS

for

Student Anthony Okiemute

Fall 2014

Life-cycle assessment of slop water management in challenging offshore drilling operations

Livsløpsvurdering av slopvannsbehandling fra krevende boreoperasjoner

Background and objective

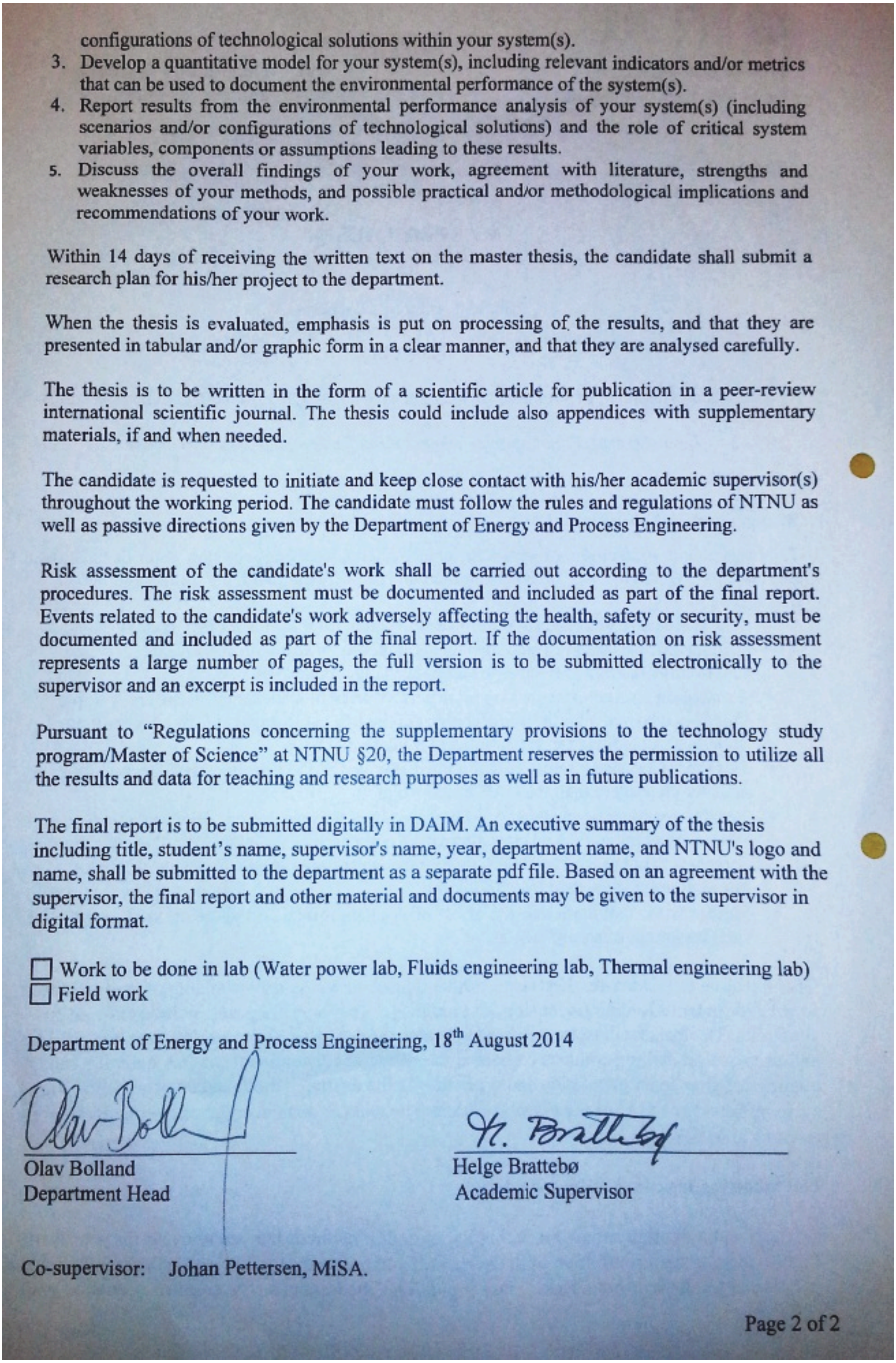
The background of this master thesis is the environmental challenges of slop water management from drilling. This issue was already examined in a project work, with the following main findings:

- There are large potentials to minimise slop water volume at source by up to 45%.
- Life-cycle assessment of slop management measures also indicates sizeable environmental improvements; for climate change impacts up to 63%.
- Evaluating a set of offshore slop management technologies, aimed at different slop qualities, showed significant differences in the life-cycle impact of each technology, indicating potentials for separation and treatment at site.
- For the treatment of lightly contaminated slop water, the filtration-based technology was a better alternative than the DAF-based technology.
- For the treatment of moderately contaminated slop water, the emulsion-breaking treatment technology is a better alternative compared to the centrifuge –based technology for impacts not related to toxicity, while the centrifuge-based technology is a better alternative for impacts related to toxicity.
- Further work should include the effect of discharges made off shore, as well as from the final treatment of sludge wastes.

The objective of this master thesis is to further contribute to the understanding of environmental impacts of potential solutions for slop water management for drilling rigs in different context situations. The thesis will examine chosen options for design of slop water management in artic and deep-sea oil drilling contexts compared to drilling in conventional context, quantities and qualities of slop water generation and types during the drilling period, and environmental life cycle impacts (by LCA) of the given solutions. The work is done in collaboration with on-going research at MiSA.

The following tasks are to be considered:

1. Carry out a literature study on, technologies and/or methods that are relevant for your work.
2. Provide a systems definition of the system(s) you are analysing, including description of goal and scope, system boundaries, data inputs and assumptions, for selected scenarios and/or



configurations of technological solutions within your system(s).

3. Develop a quantitative model for your system(s), including relevant indicators and/or metrics that can be used to document the environmental performance of the system(s).
4. Report results from the environmental performance analysis of your system(s) (including scenarios and/or configurations of technological solutions) and the role of critical system variables, components or assumptions leading to these results.
5. Discuss the overall findings of your work, agreement with literature, strengths and weaknesses of your methods, and possible practical and/or methodological implications and recommendations of your work.

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his/her 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 analysed carefully.

The thesis is to be written in the form of a scientific article for publication in a peer-review international scientific journal. The thesis could include also appendices with supplementary materials, if and when needed.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

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, 18th August 2014

Olav Boll

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Department Head

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Page 2 of 2

Dedicated to the loving memory of Lucky and Daniel Okiemute

Always and forever cherished

Abstract

Offshore oil and gas drilling operations generates slop water, which are formed when wastewater originating from multiple sources becomes contaminated with drilling fluid components and have to be disposed or treated prior to discharge in compliance with local discharge regulations. The logistics and treatment of slop water have been suggested to represent a significant part of the life-cycle environmental footprint of offshore drilling operations but poorly understood due to lack of information regarding volumes, sources and technology descriptions to properly model slop waste treatment technologies with life-cycle assessment.

In this thesis, the environmental impacts of offshore injection disposal and a range of slop water treatment technology options applied offshore and onshore for the treatment of different types and volumes of slop water were evaluated using life cycle assessment (LCA). The offshore treatment technological set-ups were filtration, dissolved air flotation (DAF) and centrifuge based treatment technologies, while the onshore treatment system involves a combination of chemical and physical treatment processes. The sources, characteristics and volume estimates of slop water treated by the identified treatment technologies were described based on four wells scenarios drilled within the Norwegian continental shelf which includes a normal, deep-water, and high pressure high temperature (HPHT) well, all of which were partly drilled with an oil based mud (OBM) and an arctic well drilled using only water based mud (WBM).

The results of the study showed that offshore treatment of slop is a better alternative to offshore injection and onshore treatment with the DAF system emerging as the best alternative overall. When slop cannot be handled at source on the rig, onshore treatment will be a better alternative to offshore injection. The disposal or recycling of oil present in slop water has a significant effect on the environmental performance of the treatment systems. A comparison of the normal well with the three other well scenarios highlighted that the HPHT and deep-water have relatively higher impacts due to the high volumes of slop water generated by both wells. The significant impact contributions of logistics when slop water is sent onshore was highlighted by the deep-water and arctic well scenarios which both has the longest distance from field to shore. The arctic well scenario offshore treatment impacts were the lowest due to the use of WBM only for drilling, thereby highlighting the significant effect of OBM use on slop water treatment impacts. The benefits of using natural gas and onshore electricity (where applicable) instead of diesel as a source of energy when handling slop offshore was also demonstrated by sensitivity analysis.

The findings of this study offers new and useful information that allows for the better assessment of offshore slop water management options which also serves as a useful input in the decision objectives used by stakeholders for the overall environmental evaluation of offshore drilling activities.

Acknowledgement

This work will not be a reality without the opportunity of working and collaborating with MiSA AS (now part of Asplan Viak AS). I am highly grateful for the opportunity and to everyone at MiSA, especially my co-supervisor, Johan Pettersen for their wonderful support, encouragement and friendship.

My heartfelt gratitude also goes to my supervisor, Prof Helge Brattebo of the Industrial Ecology Programme for his guidance, patience and understanding.

I will also like to express my profound appreciation to Torgrim Svensen at Statoil AS, Bjornung Jensen and Martin Toft both at Halliburton, John Eirik Paulsen, Alberto Gauneri and Hanjo Ledgsiter all at ENI Norge, Hans Magne Hestvik at SAR Gruppen, and my very good friend Julius Chinwenke Mba at Halliburton for their time and willingness to assist with relevant information and expertise opinions, which has greatly enriched this work.

And finally to Kristina and Cuba, your support and perseverance as well as the love and warmth radiated daily from afar, saw me to the end of this. I am forever indebted to you both.

Anthony Okiemute

Trondheim, January 2015

Table of contents

List of appendices

List of figures

List of tables

ABBREVIATIONS

BTEX - Benzene, toluene, ethylbenzene, and xylenes
BOE- Barrels of oil equivalent
COD – Chemical oxygen demand
DAF – Dissolved air flotation
GHG – Greenhouse gas
HPHT – High Pressure High Temperature well
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 in
SBM – Synthetic based mud
TCC – Thermomechanical cuttings cleaner
TOC – Total organic carbon
VOC – Volatile organic compound
WBM – Water based mud

1.0 INTRODUCTION

1.1 Background

Global energy demand has increased inexorably in the last century and it is projected to rise further by over a third by 2035 mainly as a result of growing demand in faster growing economies such as China and India. Fossil fuels - mainly oil - also continue to dominate the global energy mix despite recent modest increase in the share of renewables in both production and consumption (IEA, 2012).

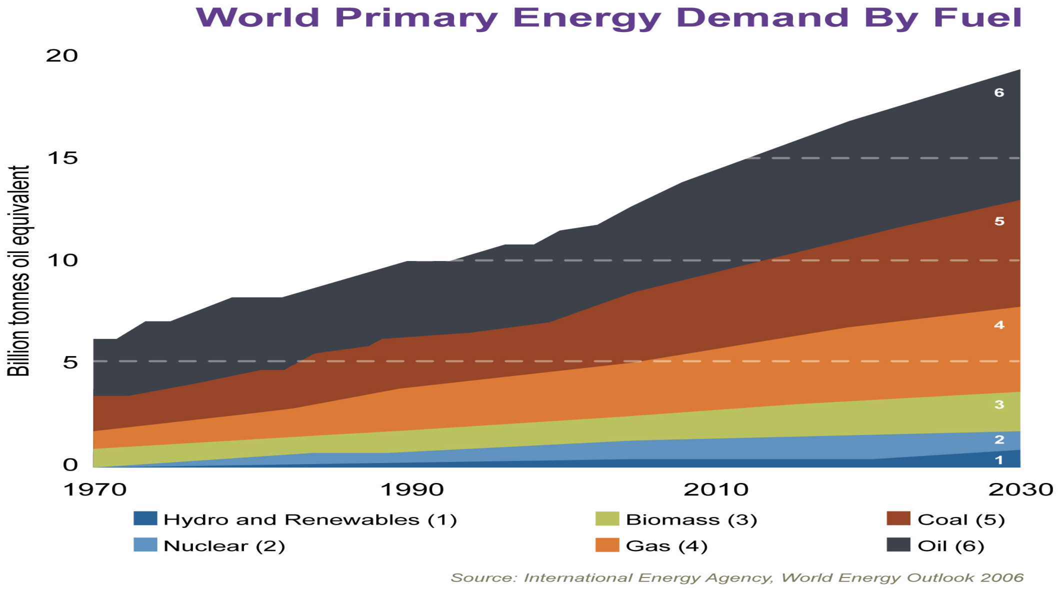


Figure 1.1 World primary energy demand by fuel. (Source: IEA, 2012)

As a result of natural decline in oil production from existing oilfields, the industry has shown a growing desire to target undeveloped fields located in challenging new environments in order to meet growing demand. Globally, undeveloped oil and gas fields are estimated to contain 1.4 trillion barrels of oil equivalent (boe) and these include hard-to-reach deepwater areas, and other challenging new frontiers such as the arctic, all of which have been inaccessible hitherto as a result of technical, geological and political challenges (DNV, 2013). As the industry deploys improved and new exploration and production technologies to operate in these areas, it will also have to contend with a number of major concerns which includes a range of potential environmental impacts such as those relating to waste management, chemical use, climate change etc., especially in the environmentally sensitive arctic region as well as changing environmental regulatory regime and increasing financial costs (Pettersen, 2007; Akplan-Niva, 2012).

The process of drilling oil and gas wells offshore generates significant volumes of waste, which includes drilling fluids and cuttings, slop water and solid wastes (Veil, 2002). "Slop water" refers to wastewater that is contaminated with oil/hydrocarbon when drilling with oil-based muds (OBM) and synthetic-based mud (SBM), while “Slop mud” is generated when OBM/SBM is contaminated with water. Both represent a significant fraction of offshore drilling waste (Ivan and Dixit, 2006). The volume and type of slop generated tend to vary from one drilling operation to another due to varying drilling conditions and can be handled offshore or sent to shore for treatment or disposal. However, as drilling operations ventures into challenging and sensitive environments such as deep-waters and the arctic, coupled with an increasingly stringent regulations governing offshore discharges, there is a growing focus not just on the associated financial cost but also on the need to ensure that drilling waste are equally managed in an environmentally acceptable/friendly manner. The application of life-cycle concept such as the use of life cycle assessment (LCA) to evaluate slop management approaches/options can offer useful and broader insights into the environmental impacts associated with the various approaches that can also inform some of the decisions aimed at addressing the highlighted environmental concerns.

1.2 Literature review

A considerable number of studies relating to the application of life cycle concepts, particularly LCA, to evaluate environmental impacts within the field of wastewater treatment have been published indicating a growing interest in LCA as a useful tool to better understand the wider environmental impacts of design and operation decisions (Guest et al., and Larsen et al., 2010). A review of such studies by Corominas et al. (2013) reported on 45 papers that have been published using various databases, boundary conditions and impact assessment approach for result interpretation. Whilst majority of the studies focused on municipal wastewater planning, only one paper, authored by Vlasopoulous et al. (2006) reported on LCA of wastewater technologies for petroleum process waters.

However, there exist a number of case studies relating to the direct or indirect application of life cycle approaches to oil and gas exploration and production. Elcock, (2007) summarized 12 of such case studies covering a range of topics such as environmental effects of drilling on the environment, drill cuttings management, drilling fluids management, site remediation, and greenhouse gases. A more recent study was conducted by Pettersen et al., (2013), in which an LCA model was presented for offshore drilling operations to describe some of the environmental loads associated with the manufacture of all input materials, steel and chemicals, together with the energy requirements for rigs, vessels and waste treatment.

With regards to oil and gas E&P drilling waste management, most of the studies identified above are mainly focused on drilling cuttings and spent fluids management with little or no attention/emissions data on slop water treatment and logistics. However, the study by Pettersen et al., (2013), indicated a reasonable contribution from slop water for both greenhouse gas (GHG) emissions and human toxicity as shown in figure 2.

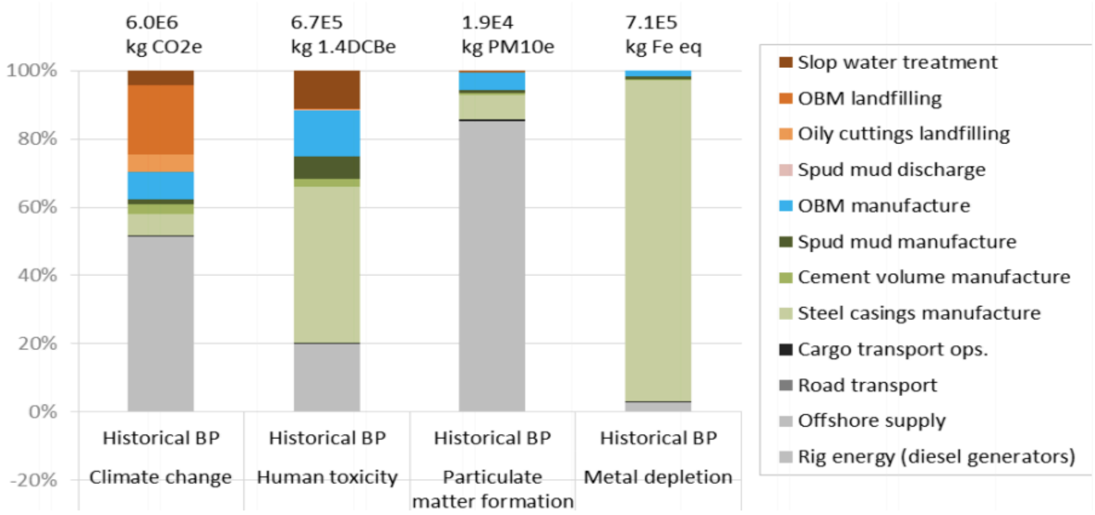


Figure 1.2. Distribution of environmental footprint for an offshore drilling operation based on historical best practice (Source: Pettersen et al., 2013)

Besides the lack of LCA application to evaluate oil and gas slop water treatment emissions, there is also currently a lack of detailed information regarding volumes, sources and sinks, and technology descriptions to properly model slop waste treatment technologies with LCA. However, a recent study by Massam et al., (2013) presented how the variability in discharge criteria relating to slop water in various countries, together with slop chemical characteristics, influences treatment methods/technologies, as well as available offshore and onshore slop treatment technologies for slop water. As indicated by the highlighted studies, LCA can serve as a useful tool to elucidate the wider environmental impacts of slop water management approaches, which can add scientific input to drilling waste management decision-making process for different drilling operations.

1.3 Structure of the work

Chapter 2 provides an overview of drilling operations and describes the sources of slop water generated during drilling operations. An overview of the various slop management approaches both offshore and onshore was also presented in this chapter.

In chapter 3, the general framework for life cycle assessment was introduced and discussed.

In chapter 4, the drilling operations scenarios as well as volume estimates and the foreground system boundaries for the treatment systems are described. The study goal and scope, functional unit, inventory analysis and impact assessment are also presented. A material flow balance for the composition of slop water during treatment treatment was also presented.

In Chapter 5, the results from the life cycle impact assessment and sensitivity analysis are presented and explained.

In chapter 6, interpretations and discussion of comparative assessment results and uncertainties associated with the study are presented.

In chapter 7, conclusions for the study and recommendation for future work is made.

1.4 Objectives

The overall aim of this master's research study is to further contribute to the understanding of the environmental impacts of potential technological solutions for slop water management in different offshore drilling operations. Hence the objectives to be achieved by the study are:

- To map and describe the sources, characteristics and volume estimates of offshore drilling slop water based on the drilling of a normal well compared with other wells drilled in a more challenging deep-water and arctic environment within the Norwegian continental shelf.
- To identify and describe possible slop water treatment/disposal technological solutions used offshore and onshore, which should also include a number of possible treatment technology options/set-ups that can be deployed in different offshore drilling operations.
- To evaluate the environmental implications of the treatment technology options described using environmental life cycle assessment (LCA) and highlight key parameters that influences slop water management between the well scenarios.

1.5 Scope and limitations

The scope of this work is defined by the scenarios investigated and forms the basis of the conclusions made. The well scenarios and slop water type and volume estimates described are based on activities within the Norwegian continental shelf but can also be related to similar operations in other countries.

The term slop is often loosely used in place of "slop water" or "slop mud" which are actually two different type of waste stream. Slop waste with solids and oil content higher than that, which is defined in this work, is outside the scope of the study. The limitations of this study with regards to data quality and uncertainty are discussed in further details later in the work.

2.0 OFFSHORE DRILLING OPERATIONS AND SLOP WATER MANAGEMENT

2.1 Offshore drilling operations

The operations of drilling a well into a potential reservoir is fundamentally the same process for both onshore and offshore systems. In an offshore system the drilling is performed by a drilling rig mounted on either a floating or a stable offshore platform that may be permanently or temporarily fixed to the seabed (NPC, 2011). Drilling is commonly accomplished using a rotary drilling method in which a drilling pipe/string with a rotating drill bit attached to the bottom cuts through the rock and grind it into small pieces or cuttings. At the same time, a drilling fluid is fed down the drill pipe/string where it sprays through jets pushing the cuttings away. Then the fluid and the cuttings are forced back up to the surface through the space between the outside of the drill pipe and the inside of the hole referred to as annulus (Neff, 2010). There are two types of drilling activities performed during oil and gas operations: exploratory and development. The exploratory drilling refers to those operations involving the drilling wells to determine potential hydrocarbon reserves. Development drilling, on the other hand, refers to those operations involving the drilling of production wells following the discovery of hydrocarbon reserve (EPA, 2000).

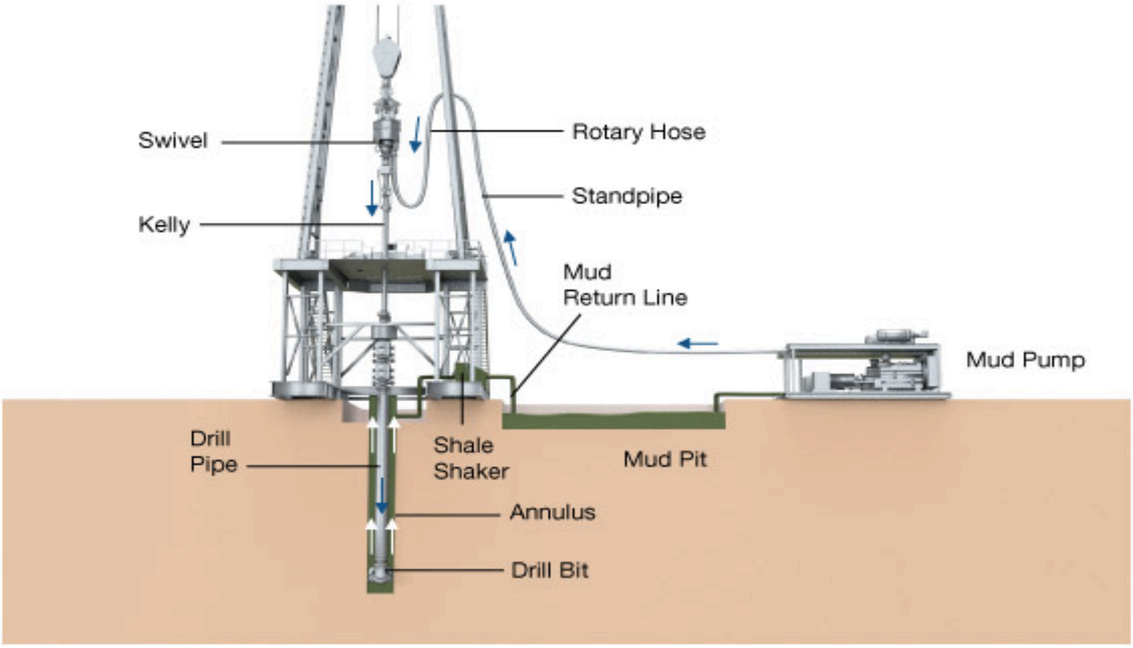


Figure 2.1 Schematic diagram of a rotary drilling process and drilling mud circulation system (source: Petroleumonline, 2014)

The main stages/sequence of offshore drilling operations are briefly described below:

i. Spudding: the term describes the beginning of drilling operation during which a large diameter hole is drilled or 'spudded'. Fluid containing seawater is usually used for this drilling and the fluid and cuttings are not returned to the rig deck but deposited near the well on the surface of the seafloor. The 36" and 26" sections are often drilled in this manner (Neff, 2010; NPC, 2011).

ii. Casing and *cementing*: When the well is spudded, a steel casing, referred to as a conductor casing (usually no more than 20-50 feet long) is installed in the well hole and cemented into place to prevent top of the well from caving in and isolate the well from the producing formation. As the well is drilled deeper, due to changes in rock strength or pressure, it is protected by additional steel casings, which are successively smaller in diameter, at certain intervals. Usually the conductor casing is followed by the surface casing, and then the intermediate casing and ending with the production casing especially when significant oil is present in the formation and production is bound to happen (Devold, 2006).

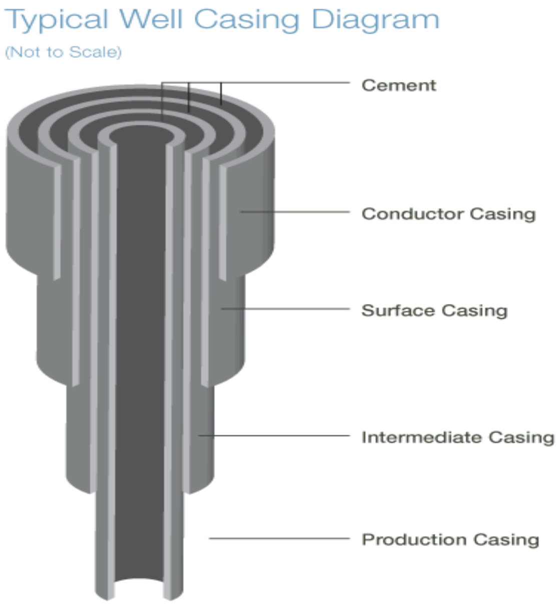


Figure 2.2 Typical well casing diagram

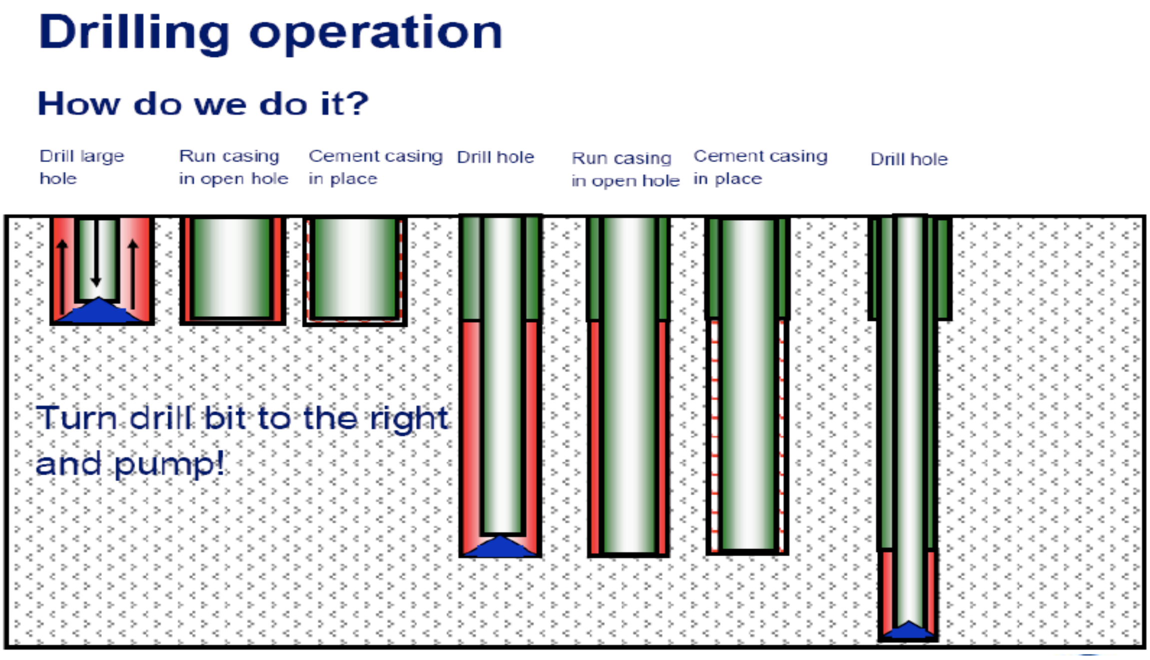


Figure 2.3 Simplified sequence of oil and gas well drilling (Nergaard, 2005)

Circulation system The circulation system is a key aspect of the drilling process and consists of the mud pumps, distribution lines and the mud cleaning and accumulation system as illustrated in figure 2 above. A pipe connection (also known as a riser) is installed between the well and the rig system resulting in a closed hydraulic circuit which allows drilling fluids to flow from the surface through the drill string/pipe to the bottom and then back to the rig deck via the borehole annulus as demonstrated by the arrows in fig 2.1. Separation of cuttings from the fluid takes place in the shale shaker before the fluid is being re-injected into the hole. The mud pump ensures the circulation of mud/fluid from the mud pit to the bottom of the hole via the rotary hose and drill string (ENI, 2008).

2.2 Drilling chemicals

A wide range of chemicals is employed during oil and gas field drilling, production, well treatment and completion activities. Chemicals used during drilling can be grouped into the following categories:

i. Drilling fluids: Also referred to as drilling muds, they are used to aid the drilling process and serve a variety of functions which includes:

- Controlling formation pressures
- Removing cuttings from wellbore
- Sealing permeable formations during drilling

- Cooling and lubricating the drill bit,
- Transmitting hydraulic energy to down hole tools and bit
- Maintaining wellbore stability and control

Drilling fluids systems have a continuous phase, which is a liquid and a discontinuous phase consisting of solids. There are also gas phase systems, made either by design or as a consequence of formation gas entrainment. The continuous phase are used to classify drilling muds indicating that the fluids are a blend of liquid and solid components, each designed by manipulating a specific property of drilling fluid such as its viscosity and density. The main types of drilling fluid/mud systems are (Williamson, 2013):

a. Water-based muds (WBM) – the base (continuous phase) primarily consists of fluid, which may be fresh water, seawater, or brine making up about 85 to 90% of the total volume blended with 10 to 15% of various components including barite, potato or corn starch, cellulose-based polymers, xanthan gum, bentonite clay, soda ash, caustic soda and salts (NPC, 2011). They are the most widely used, especially for the upper sections of the well but their technical performance is limited in deeper and challenging wells. They are reported to have limited environmental effect partly due to the non-toxicity of clay and bentonite, while the heavy metals components (e.g. Ba, Cd, Zn, and Pb) are bound in minerals and as such have limited bioavailability. Discharge of WBM to sea has been reported to temporarily affect benthic organism by smothering approximately 100 feet from discharge and species diversity to a distance of about 300 feet from discharge (Williamson, 2013; NPC, 2011).

Table 3.1 Main components of water-based fluid (NPC, 2011)

Component	Use	Ecotoxicity
Aluminium stearate	Defoamer	Non-toxic, insoluble
Barite Weighting agent	Weighting agent	Non-toxic, insoluble, non-biodegradable
Bentonite Viscosifer	Viscosifer	Non-toxic, insoluble, non-biodegradable
Calcium carbonate	Bridging, loss of circulation	insoluble
Caustic soda pH and alkalinity control	pH and alkalinity control	Soluble, corrosive
Cellulose based polymers Fluid loss control	Fluid loss control	Insoluble, non-toxic
Citric acid pH control	pH control	Soluble, low toxicity, irritant
Diesel oil pill (< 0.1 % mud volume) Stuck pipe spotting fluid	Stuck pipe spotting	Slightly soluble, 96 hr LC50 >0.1-1000 ppm
Gilsonite (asphalt based) Lubricant, fluid loss reducer	Lubricant, fluid loss reducer	Low toxicity, slightly soluble
Gluteraldehyde (0.01% mud vol) Bactericide (biocide)	Bactericide (biocide)	Noted for its toxic properties, irritant
Lime	Carbonate and CO2 control	Slightly soluble, non-toxic, irritant
Organic synthetic polymer blends	Filtrate reducing agent	Non-toxic, 96 hr LC50 >500 ppm
Palm oil ester Lubricant, stuck pipe pills	stuck pipe pills	Slightly soluble, biodegradable
Potassium chloride	Shale / clay inhibitor	Soluble, non-toxic
Soda ash	Alkalinity, calcium reducer	Soluble, non-toxic
Sodium bicarbonate	Alkalinity, calcium reducer	Soluble, non-toxic
Xanthan gum	Viscosity, rheology	Soluble, non-toxic

b. Oil-based muds (OBM) - were developed to address some of the technical problems associated with WBM and the continuous phase may consist of diesel and conventional oil mineral. Advantages of OBM include faster drilling rates due to better lubrication, offer greater extended reach drilling, better suited for long and deviated wells and in high-pressure, high-temperature (HPHT) reservoir, reduces drilling waste and result in fewer rig days overall (HSE, 2000, NPC, 2011). Disadvantages include higher toxicity compared to WBM, higher cost, waste disposal and logistical issues, displacement and clean-up as well as cement compatibility issues (OGP, 2003; Jacques Whitford Environment Limited, 2001).

c. Synthetic muds (non-aqueous) – were developed in an attempt to reduce the toxicity associated with OBM while still maintaining its technical superiority. They are formulated either with by reducing the PAH content of diesel-oil fluids or with a variant of low-toxicity oleaginous (oil-like) base such as vegetable esters, synthetic paraffin (Williamson, 2013, HSE, 2000).

Table 2.2 Main chemicals used in oil/synthetic-based fluid (NPC, 2011)

Material	Description
Base oil	Non-aqueous drilling fluids use base fluids with significantly reduced aromatics and extremely low polynuclear aromatic compounds. New systems using vegetable oil, polyglycols or esters have been and continue to be used.
Brine phase	CaCl2, NaCl, KCl.
Gelling products	Modified clays reacted with organic amines.
Alkaline chemicals	Lime e.g. Ca(OH)2.
Fliud loss control	Chemicals derived from lignites reacted with long chain or quaternary amines.
Emulsifiers	Fatty acids and derivatives, rosin acids and derivatives, dicarboxylic acids, polyamines.

ii. Cement and cement additives: Cementing operation involves the use of slurry, which is a mixture of cement, water, and chemical additives. Portland cements is commonly used and consist mainly of anhydrous calcium silicate and calcium aluminate compounds. Over 100 additives are available to adjust cement performance, which also perform similar functions as drilling fluid additives. Hence they are classified by their functions such retarders which delays cement setting time, extenders which lowers cement slurry density, weighting agents which API and ISO standards (Williamson, 2013; Macini, 2008)

iv. Wellbore and rig cleaning chemicals: A range of chemicals spacers are used to displace drilling fluid during wellbore cleaning can include a blend of polymers, barite and water, a blend of polymer with sodium, potassium, or calcium salt, a blend of viscosifiers such as xanthan gum in organic solvent, or a complex blends of monocyclic and aromatic hydrocarbon, and alcohol solvents. Detergents are also used for rig deck cleaning and often contain a blend of anionic and non-ionic surfactants (Tetra technologies, 2013).

2.3 Drilling slop water

Slop water (also sometimes referred to "*Oily wastewater*" or "*special waste"* in environmental reports in Norway) is the term used to collectively describe oil contaminated wastewater stream generated during drilling operations which originates from multiple sources and vary considerably in composition. Oil contaminated water generated from marine engineering operations away from the drilling deck are also often referred to as slop water but are considerably different from those generated during drilling operations and is not the focus of this study. The volume and type of slop water generated varies considerably from one drilling operation to another, as every drilling operation is unique in its own way. Common factors generally responsible for such variations include the nature of the reservoir geologic formation, rig configuration, operational practices, type of drilling fluids used and geographic location of target reservoir (Kaiser 2009; Massam, et. al., 2013). The volume and type of slop water generated also, to large extent, influences how they are managed.

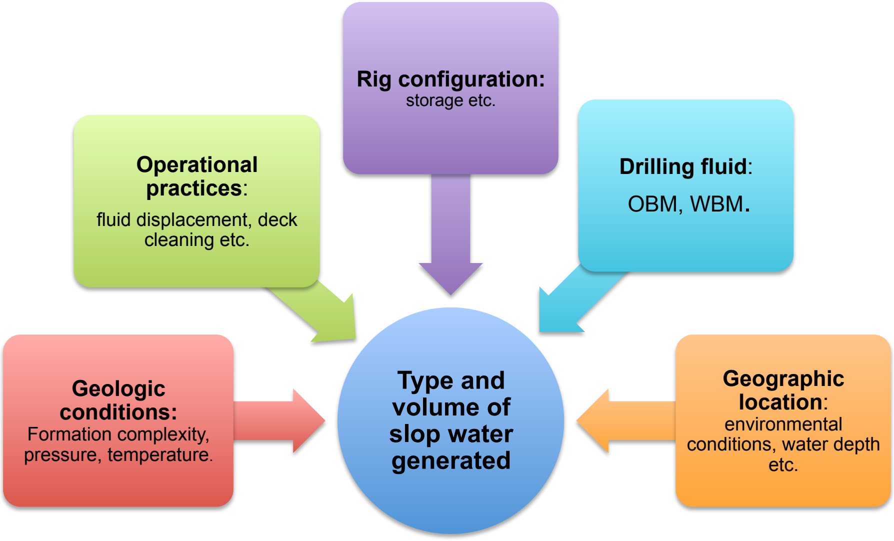
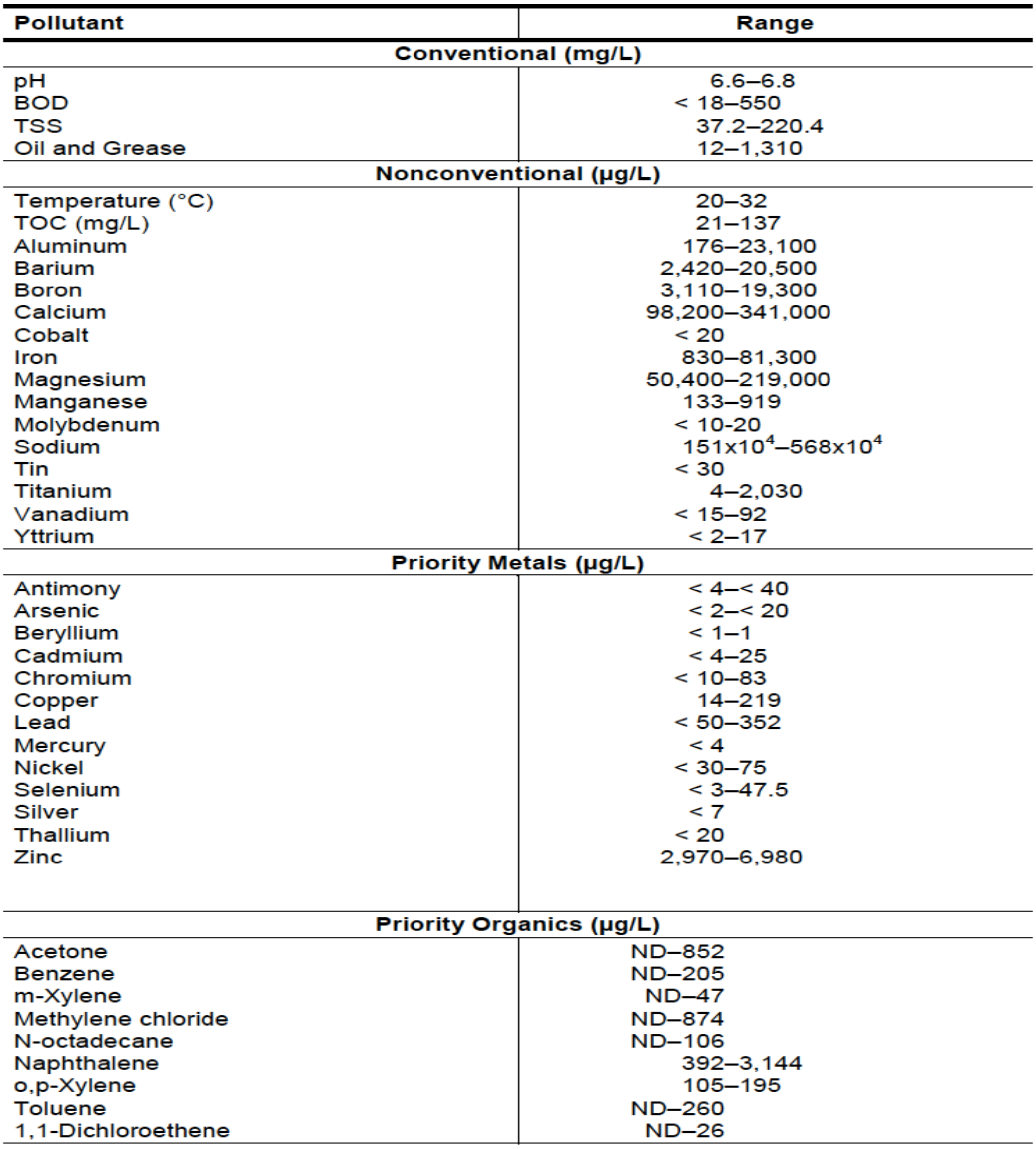


Figure 2.4 Main factors influencing the type and volume of slop water generated during offshore drilling operations

2.4 Composition and sources of slop water

Slop water is commonly described based on its composition of water, oil and solids, which is generally considered to be around 80%, 10% and 10% respectively (Bilstad et al., 2012). However the oil and solids can vary from low oil and solids contaminated slop water containing less than 1% of oil in water (or <1000mg/l oil) and less than 1% solids to a moderately high oil and solids contaminated slop water with an oil in water range of 1-35% and less than 10% solids. Complex water in oil emulsion or slop containing over 35% oil and 10% solids are considered to be heavily contaminated and more challenging to handle in a similar way as the less contaminated ones (Massam et. al., 2013). Slop water also contains a mixture of organic and inorganic pollutants ranging from aliphatic and aromatic hydrocarbon and heavy metals, which are all well known to be toxic to aquatic life. Slop can also contain surface-active agents used for rig deck cleaning. A list of organic and inorganic pollutants present in an untreated deck drainage slop water generated during an offshore well drilling operation is presented in table 2.3 below.

Table 2.3 Pollutants present in untreated deck drainage slop water (EPA, 2012)



Pollutant	Range
Conventional (mg/L)	
pH	6.6–6.8
BOD	< 18–550
TSS	37.2–220.4
Oil and Grease	12–1,310
Nonconventional (µg/L)	
Temperature (°C)	20–32
TOC (mg/L)	21–137
Aluminum	176–23,100
Barium	2,420–20,500
Boron	3,110–19,300
Calcium	98,200–341,000
Cobalt	< 20
Iron	830–81,300
Magnesium	50,400–219,000
Manganese	133–919
Molybdenum	< 10-20
Sodium	$151x10^4$–$568x10^4$
Tin	< 30
Titanium	4–2,030
Vanadium	< 15–92
Yttrium	< 2–17
Priority Metals (µg/L)	
Antimony	< 4–< 40
Arsenic	< 2–< 20
Beryllium	< 1–1
Cadmium	< 4–25
Chromium	< 10–83
Copper	14–219
Lead	< 50–352
Mercury	< 4
Nickel	< 30–75
Selenium	< 3–47.5
Silver	< 7
Thallium	< 20
Zinc	2,970–6,980
Priority Organics (µg/L)	
Acetone	ND–852
Benzene	ND–205
m-Xylene	ND–47
Methylene chloride	ND–874
N-octadecane	ND–106
Naphthalene	392–3,144
o,p-Xylene	105–195
Toluene	ND–260
1,1-Dichloroethene	ND–26

The sources of slop water generated during an offshore drilling operation are described below:

a. Deck drainage: This is used to describe any wastewater collected by the drains system located in the hazardous areas of the rig such as the rig floor and mud pit area. Such wastewater originates from rainwater, melted snow, fire water, wash-down water including spillages and equipment drains or leaks from all deck levels, equipment dip trays and bounded areas. Whilst rainwater from non-hazardous areas such as the living quarters of the rig are typically discharged without treatment, drain water from hazardous area likely to be contaminated with oil, and as such are prohibited from discharge unless the oil content is reduced to permissible levels. Hence, it is required that this drain water must be routed to a dedicated collection system such as a slop tank for further handling (NORSOK S-003, 2005). Slop water from this source usually contain less than 1000ppm (1% v/v) and less than 1% v/v solids and its volume depends on the weather condition, drilling duration, the use of OBM, red or black chemicals which are generally prohibited from discharge offshore.

b. Cement displacement operations: During the cementing of the casings as described in section 3.1.ii (also referred to as primary cementing), cement slurry is pumped down the wellbore to displace the earlier used drilling fluid from the wellbore and a displacement fluid such as a drilling fluid is then used to displace the cement into the annulus where it is allowed to set. Due to the incompatibility of cement slurries and drilling fluids, they are often kept apart using chemical washes and spacer fluids, which are pumped after the drilling fluid and before the cement slurry as shown in figure 3.5. A typical chemical wash and spacer sequence comprise a base fluid, a dispersant, a carrier spacer, and a separation spacer. When oil based drilling fluid is being displaced, the chemical washes and spacer fluids as well becomes contaminated with invert emulsion drilling and as such contain water wet OBM, solids, dispersed oil and emulsifiers thereby ending up as slop with an estimated oil content range above 1% but less than 35% and less than 10% solids.

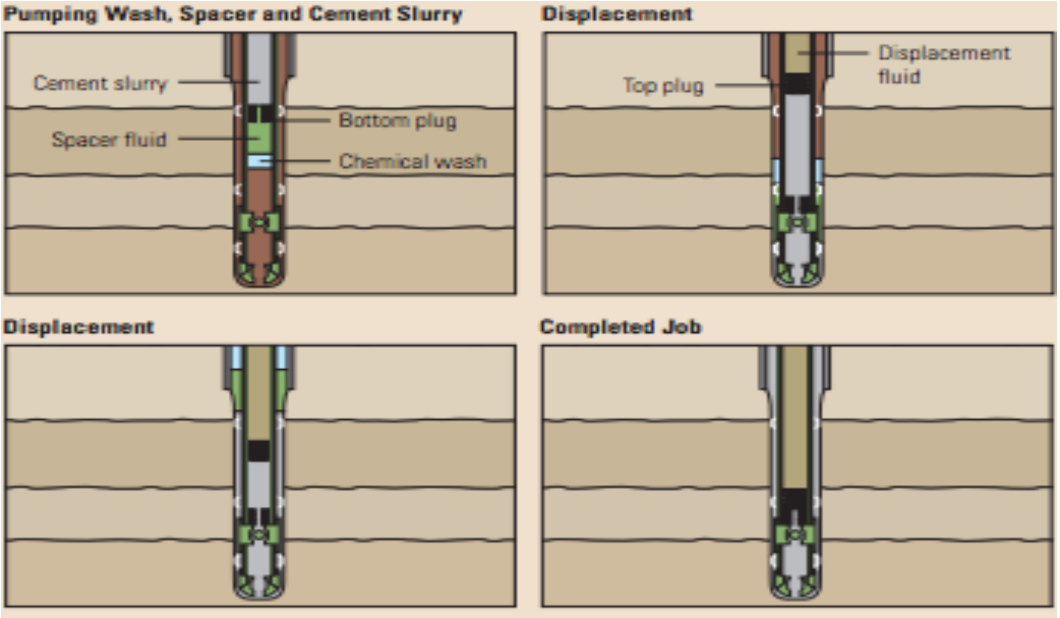


Figure 2.5. An illustration of fluid displacement and casing cleaning during cementing operation (source: Nelson, 2012)

c. Wellbore clean up operation: After drilling an exploration well and depending on the estimated quantity of oil in the formation, it can either be plugged with cement and abandoned or prepared for oil production, which is also referred to as well completion. In both cases, if the last section of the well was drilled with oil based fluid, it is usually displaced from the wellbore and riser with seawater/brine, which becomes contaminated with oil and generating slop waste. The wash pills, spacers as well as the seawater pumped directly behind it picks up a significant quantity of fluid are more contaminated with an estimated oil content range above 1% but less than 35% and less than 10% solids. However, the middle phase of the seawater will be less contaminated and resembles the deck drainage slop with estimated 1% oil and 1% solids.

c. Surface tanks and pits cleaning operations: The cleanout of drilling fluids tanks (mud pits) on the rig or storage tanks on the supply / standby boats, both offshore and onshore, also generate slop due to the contamination of wash water with fluids. The volume of wash water and level of sediment generated will vary considerably depending on the cleaning method, which could be manual (low volume) or automatic (high volume) and if the water is recycled or not. The wash water portion has oil and solids composition similar to the deck drains slop water and are collected in the open drain or separated from the cleaning water following the sedimentation of the solid portion, depending on the rig practices. The heavily contaminated portion, which contains over 35% oil and over 10% solids, is usually collected in a separate dedicated tank and most likely send onshore for treatment or disposal (Eia and Hernandez, 2006).

2.5 Slop water management

There are a number of options available for handling slop water which include handling at source by offshore re-injection, treatment and discharge of treated water that meets discharge regulation and transport to shore for treatment and disposal (Massam et al., 2013). In the NCS, offshore re-injection and onshore treatment are more common practices relative to offshore treatment (Svensen and Taugbol, 2011).

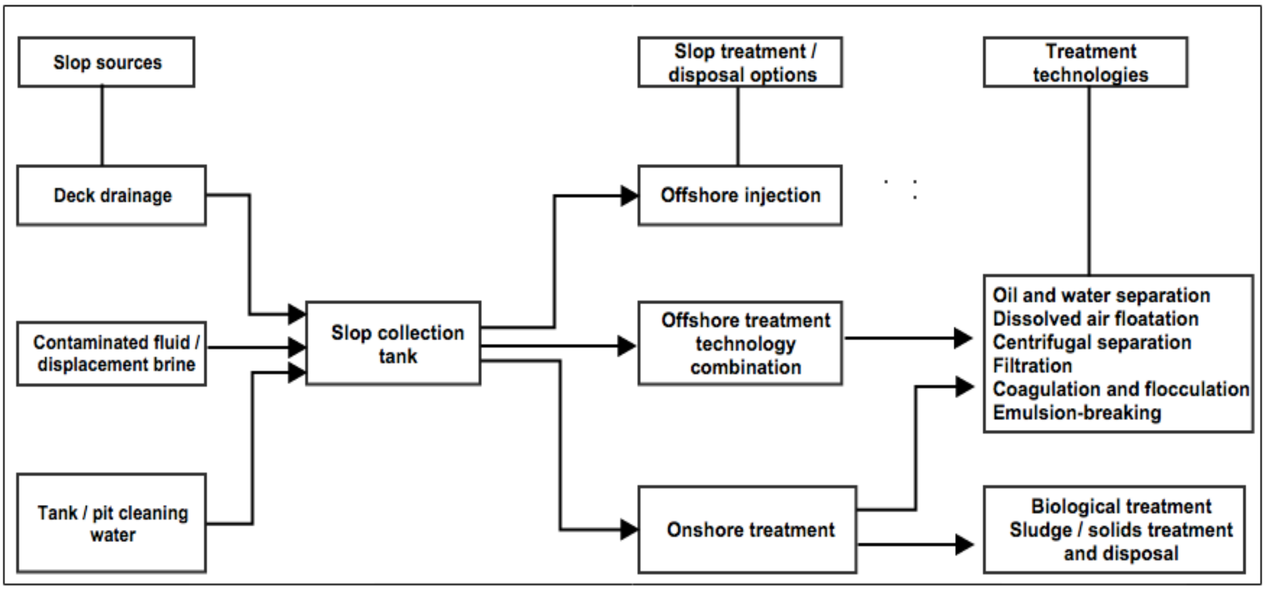


Figure 2.6. Generalised flow sheet of slop water sources and management approaches

2.5.1 Offshore injection

Historically, the re-injection of cuttings with slop water has been a preferred method for the disposal of drilling waste by the industry and it is considered as an economical and environmentally friendly option (Bilstad et al., 2012; Saasen et al., 2001). It entails the grinding of cuttings to form slurry with the addition of seawater or slop water and chemicals such as a viscosifiers, which is then pumped downhole into one of three types of well which are via the annulus of an existing well, directly into a redundant well or directly into a dedicated well as shown in figure 2.7 (Saasen et al., 2000).

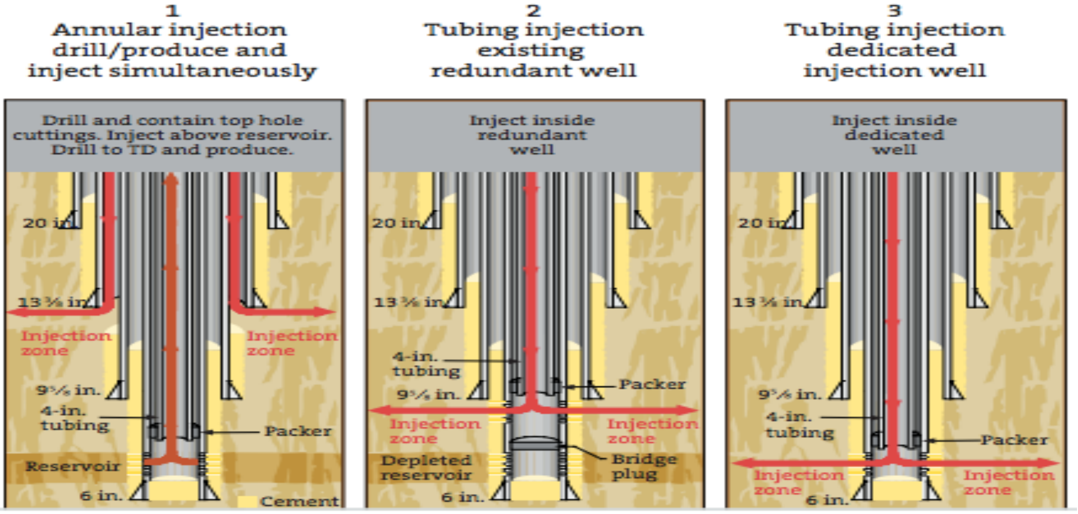


Figure 2.7. Well options for injecting cuttings

The first technique (annular injection) was previously widely practised in the NCS, however recent incidents of leakages to the surface has led to new legislation requiring that re-injection be performed using dedicated injection wells, leading to a limitation to injected volumes and complete halt of re-injection in most cases in the NCS between 2011 and 2012 (Saasen et al., 2014). However advances in technology and renewed interest in the method saw the drilling a staggering 28 injection wells in the NCS in 2013 (Oljedirektoratet, 2014). The water cuttings ratio often used for slurrification is 3:1 but higher water fractions are common. In the NCS, grinding can be achieved either by using centrifugal pumps, cutting mills in the slurrification unit or ultrasonic technology (Saasen et al., 2000). The process also requires that careful consideration is given to the types, quantities of waste, well design and integrity (NPC, 2011).

2.5.2 Offshore treatment

The challenges with slop injection and stricter environmental regulation has increased the focus on suitable technologies for treating slop waste at source and reducing the volume of waste that needs to be shipped onshore. The optimal treatment methods required depends on the nature of slop water stream, which can be complex and vary significantly. Treatment can be achieved by chemical or physical processes, or a combination of both. The treatment processes can include one or two main stages depending on the contamination level of the slop water being treated. The stages are described below (Ivan and Dixit, 2006):

1. Separation stage: involve processes used to separate mud and water, which are then transferred to separate holding or treatment vessels for further processing. Separation method is either a chemical or physical process or a combination of both.

2. Water treatment stage: if separated water or slop collected directly during drilling does not meet discharge limits, it is treated and either discharged in line with the regulations or reused where possible Commonly used physical and chemical treatment methods are briefly described below.

2 a. Physical treatment processes

i. Oil and water separation by settling

Separation by settling or gravity is the simplest and widely used technology especially for lightly contaminated fluid due to their low oil and solid content. It is only effective for the bulk removal of free oil, and not for emulsified oils. It entails holding wastewater under quiescent condition long enough to allow the oil droplets, which have lower specific gravity than water (oil from drilling slop is about 0.76 - 0.86g/cm3) to rise and form a layer on the surface where they are removed using skimmers, baffles, plates, slotted pipes or dip tubes. Solids settle and collect at the bottom where they can be removed. Storage tanks or specially designed tanks can be used for this process. Lamella plates can also be used to improve separation rate of solid from oil (EPA, 2000).

ii. Dissolved air floatation

The technology is based on floatation, a process that uses fine bubbles to induce suspended particles to rise to the surface of a tank where they can be collected and removed. Gas bubbles attach to particles thereby reducing their specific gravity and causing them to float. Fine bubbles are generated in DAF by forcing air into solution under elevated pressure followed by pressure release. Major components of a conventional DAF unit include a centrifugal pump, a retention tank, an air compressor, and a flotation tank. Commonly used with gravity sedimentation to remove suspended solids and dispersed oil from oily wastewater, as oil-wet solids are difficult to remove from wastewater using gravity sedimentation alone (EPA, 2000; Sharaai et al., 2010). A schematic illustration of a typical DAF unit is shown figure 2.8.

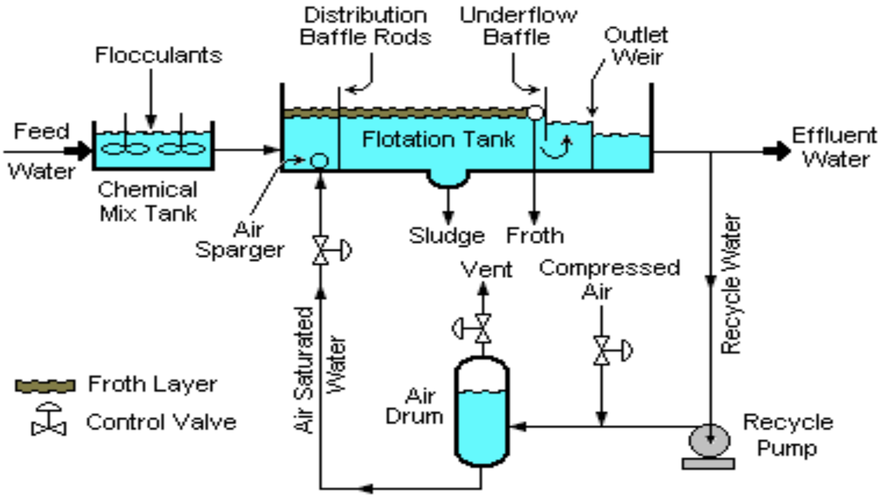


Figure 2.8 Schematic illustration of typical DAF unit (Wikipedia, 2015)

iii. Centrifugal separation

This method is based on increasing the gravitational force as a means enhancing gravity sedimentation. The common types are the 2-phase decanting centrifuges/decanters, used to remove coarse and heavy solids from fluids and the 3-phase decanter, which can separate oily waste into water, oil and solids. There is also the disc-stack centrifuge used for the removal of finer solids and oil using an extremely higher centrifugal force compared to the decanter centrifuge. The technology is commonly present on the rig as part of the bilge water treatment system and is often used to treat produced water. Hydyroclone is another type of centrifugal technology that has been used offshore (Massam et al., 2013). A schematic illustration of a 3-a typical 3-phase decanter is shown below.

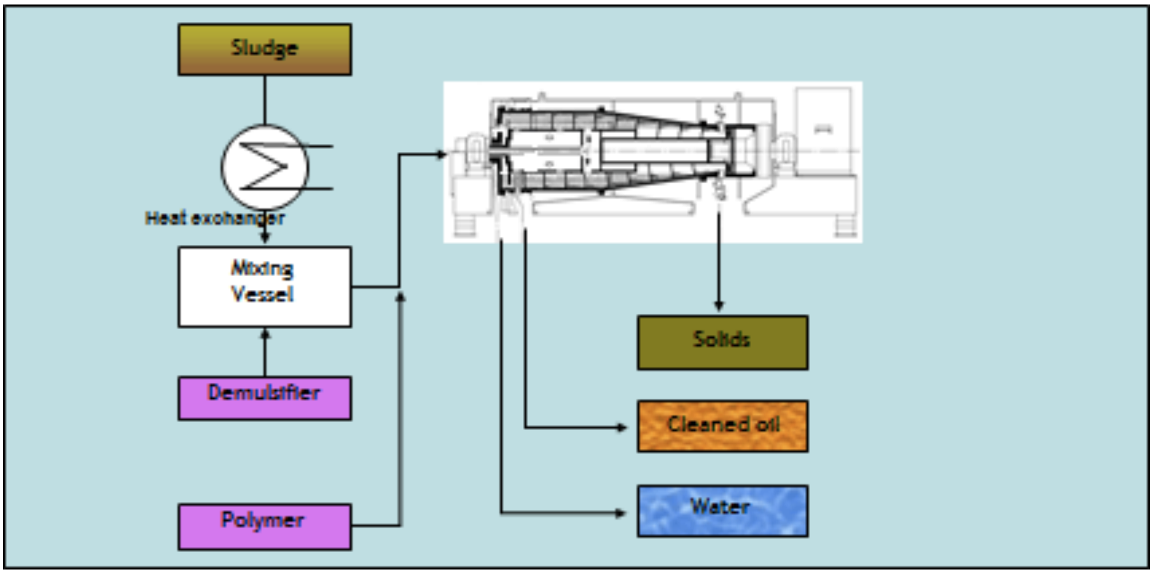


Figure 2.8 Schematic illustration of typical 3-phase decanter centrifuge (Hiller, 2015)

iv. Filtration

Filtration technologies are widely used to treat oily water either as a stand-alone filtration system or as filters integrated into a treatment package that uses other upstream technology to treat slop before a final polishing filtration step. Commonly used filters include bag filters, oil-absorbing cartridges that are made of polypropylene or may also contain polymer-modified cellulose or amino-organo modified clay to absorb hydrocarbon. Other types of filters used are coalescing filters that comprise lipophilic media used to remove oil and impurities and activated carbon/charcoal filters that absorb contaminants including organic nonpolar substances. The use of membrane technology has also been reported (M I Swaco 2004; Twinfilter, 2012).

2 b. Chemical treatment processes

Coagulation and flocculation

Coagulation and flocculation are often used interchangeably but are actually two distinct processes. Coagulation refers to the use of chemicals to neutralize the net repulsive forces that stabilize an oil droplet and prevent it from coalescing allowing it to form large agglomerates, which can be subsequently removed by sedimentation, flocculation, centrifugation, filtration or other separation methods. Commonly used coagulants are aluminium and ferric salts, lime, cationic polymers and anionic and non-ionic polymers.

Coagulant aids are also commonly used, which are additives that can be added to a destabilized oil particles to enhance the formation of large, rapid settling floc, which can then flocculate.

Flocculation on the other hand, is used to promote the aggregation and coalescing of the destabilized oil particles. Flocculation can be achieved by the stirring or agitation of water that has been chemically treated to induce coagulation (Armenante, no date)

Emulsion-breaking

This process Involve the use of emulsion breaking chemicals such as surfactants to demulsified oil/water mixture. Oily water emulsions consist of oil, water and solids combined in one emulsion. Following the addition of the emulsion-braking chemical, the content of the tank is mixed. The water and emulsion breaking surfactant will rise to the top of the tank if it is water soluble and skimmed off by mechanical means. The sludge or drilling fluid settles to the bottom of the tank and recovered. Water-soluble surfactants are preferred if the system is designed to recondition and reuse separated fluids. On the other hand, oil soluble surfactant is retained in the recovered fluid and may affect the properties of drilling fluid if it is to be reused (Ivan and Dixit. 2006, EPA; 2000; M I Swaco, 2004).

2.5.3 Onshore treatment and disposal

The treatment technology employed in onshore facilities also relies on a combination of any of the physical and chemical processes described above. They are also similar to those used offshore except that onshore facilities handle and treat significantly higher volumes and may require more consumables depending on nature of the waste stream. More so, the discharge criteria onshore covers - in addition to oil content - total organic content (TOC), pH, chemical oxygen demand (COD), heavy metals, PAH and PCBs which means that treatment systems often include extra polishing processes to meet discharge criteria. Biological treatment is another method better suited to onshore treatment and capable of removing COD and TOC in addition to the oil content. Slop water sent onshore is likely to be added to drilling fluids and treated as a single waste stream (Jensen and Toft, 2013). The volume of slop sent onshore for treatment from Statoil installations from 2008 to 2010 is given in table 2.2.

Sludge recovered from drilling can treated or disposed of in a number of ways which include thermal treatment by incineration or thermal desorption, biological treatment, disposal to landfill and in some cases they are applied to land after being stabilized and solidified. With regards to solids and sludge recovered from slop treatment, common practices in Norway is send them to landfill, however it has also been reported that such waste stream are send to other European countries such as Germany where facilities are available to further process the waste stream before disposal (DNV, 2012).

2.6 Oil recycling

The quality and quantity of base oil present in slop water (due to the use of OBM) that can be recovered for reuse depends on the type of technology used to treat slop water. Oil is present in slop water either as dispersed or free oil or in emulsion form. The dispersed or free oil has a lower specific gravity relative to water and rises to form an oil film at the surface of the water under calm conditions. The emulsion form can be stable or unstable. A stable emulsion refer to the dispersion of oil droplet within water, which are intentionally prevented from coalescing due to the presence of emulsifying chemicals, which stabilize the oil mixture (Wasterwater tech, ref). An example is the OBM system, which is stabilized with the addition of emulsifying agents alongside other chemicals such weighting agents viscosifiers etc. (Massam, et al., 2014). An unstable emulsion on the other hand contains oil dispersion that can easily settle rapidly or separate from water.

Dispersed oil can be removed from water using physical or chemical methods. Physical methods include the gravity separation and DAF. With gravity separation, the contaminated water is held in quiescent condition long enough for the oil droplets, which have a lower specific gravity, to rise and form a layer on the surface where it can be decanted off. The DAF method enhances the oil removal using the flotation process as described in section 2.a.ii and is also better suited for inducing the removal of oil wet solids which are difficult to remove by sedimentation alone and the sludge generated can be further processed using methods such as centrifugation to remove oil or disposed (wastewater).

The efficiency of oil removal by physical methods can be greatly increased with the addition of chemicals, particularly when slop water is emulsified due to contamination with emulsion drilling fluids, in which case, separation with physical methods alone will be ineffective. Whilst DAF process can be aided with the addition of chemicals such as coagulants as described in section 2.5.2, emulsified oil-water mixture treatment often involves an emulsion breaking process whereby chemicals generally referred to as demulsifiers is used to split water from drilling fluid. The emulsion breaking method is often used in conjunction with physical methods such as gravity separation, DAF and centrifugation. This approach has been reportedly used successfully to potentially recover drilling fluid from slop water both offshore and onshore, which can be reconditioned for immediate reuse in the active system or reused as raw material for drilling fluid.

2.7 Regulatory requirements

In Norway, the discharge of oily water to sea is regulated nationally through the Pollution control act and HSE regulations by the Norwegian State Pollution Control Authority (SFT). Norway is also a contracting party to the Oslo-Paris Convention for the Protection of Marine environment of the North – East Atlantic (OSPAR) through which 19 such discharges is also regulated. Under the HSE regulations, in the activities regulation (ChapterXI, Section 60), oily water has to be cleaned before discharge to sea and the oil content in water should be as low as possible, specifically not exceeding 30mg/l of water as a weighted average for one calendar month. It also stipulates that permits for the injection of oily water has to be granted according to the Pollution Control Act and for drainage, displacement and injected oily water, the amount of water and the content of oil must be measured, calculated or estimated according to OSPAR guidelines (PSA, 2014).

The OSPAR convention contains a 40mg/l limit for oil in water to be discharge (this was set lower to 30mg/l in Norway as of 2007 as stated above) but also requires that the maximum concentration of dispersed oil must not be higher than 100mg/l at any one point. The sampling regime and test method to measure the oil content in discharged water is also detailed in the OSPAR Agreement 2005/15, which provides that oil content must be measured using the Gas Chromatography – Flame Ionization Detection method. When easier and quicker methods for measuring oil content are used offshore such as the Infra-Red (IR) method, it has to correlate with the OSPAR GC-FID method (OSPAR, 2003). OSPAR also provides guidelines for chemical discharge to sea via the PLONOR list. PLONOR substances refers to substances considered to Pose Little or NO Risk to the environment based on their characteristics with regards to bioaccumulation, acute toxicity, persistence in the marine environment and endocrine effects potentials.

Efforts to further protect the marine environment, especially sensitive areas like the artic lead to the introduction of the ‘zero discharge” goal for petroleum activities, which is not necessarily numeric standard or discharge limit but rather the commitment of the goal of a zero discharge of environmentally hazardous substances using the Best Available Techniques (BAT) as outlined by the IPCC directives. Also, crucial to this commitment is the waste hierarchy which serves a guiding principle for waste management where initiatives should be prioritized in a hierarchical order of reduce, reuse, recycle, recover and disposal. (EPA, 2011; Paulsen, 2004). This can be demonstrated by efforts to minimize slop water at source as much as possible and treating volume generated at source (on the rig) allowing for discharge of clean water

3.0 LIFE CYCLE ASSESSMENT METHODOLOGY

3.1. Introduction

Life cycle assessment (LCA) is a tool used to quantify the environmental impacts associated with a product, service or process over its entire life cycle from raw material extraction through production, use and final treatment or reuse (Guinee, 2001, Corominas et al, 2013). According to ISO14040, LCA is described as the compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle, in other words, it is based on an accounting of all energy and material flows associated within a system or a process (Khan et al. 2005). Though LCA is quantitative in character, it also takes into account qualitative aspects in order to provide a comprehensive picture of the environmental impacts and a better view of the environmental trade-offs involved in products or process selection (Finnveden, 2009). The comprehensive scope of LCA is beneficial in avoiding problem-shifting, either from one stage of the life-cycle to the other, from one region to another or from one environmental problem to another which makes it a suitable tool for making informed environmental decisions (EPA, 2006).

Introduced in the 1960’s as an approach to cumulatively account for energy and resources use following concerns over their limitations, LCA has since improved as a methodology that includes emission inventory methods and environmental cause-consequence modelling (UNEP, 2005; Udo de Haes at al. 2002). This resulted in the development of numerous approaches for different disciplines. In the late 1990’s, efforts were made by the SETAC working group and other institutions to standardize LCA methodologies which gave rise to the development of LCA standards in the International Standards Organisation (ISO) 14000 series, with a revised version recently completed in 2006 (UNEP 2005; Corominas et. al, 2013).

3.2. LCA General framework

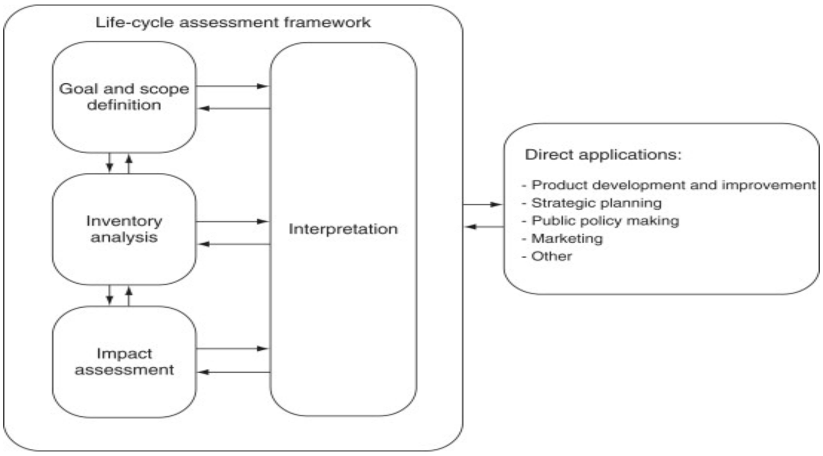


Figure 3.1 Phases of an LCA (ISO, 14040:2006)

The standard framework for LCA is a systematic approach comprising four consecutive phases: Goal and scope definition, inventory analysis, impact assessment and interpretation. An illustration of the framework is presented in the figure 3.1 (ISO, 2006).

Goal and Scope definition

The goal and scope definition phase entails defining the purpose or intended application of study (e.g., for analysis, design, information), reason for conducting the study and the audience. The scope defines the product system or process to be studied, the functions of the system and the functional unit. The functional unit is a quantitative measure of the function fulfilled by the product or process being studied. It is the quantitative reference to which inputs and outputs are related (Elcock, 2007). The system boundaries are defined by describing the processes to include, level of details based on which the requirements for data are established. Also in this stage, the methods for assessing potential environmental impacts and the impacts categories are defined.

Life cycle inventory analysis (LCI)

In the LCI phase, an inventory is established by collecting data to quantify the inputs and outputs of the system being studied. The types of data collected include inputs such as energy and material resources and outputs such as wastes, emissions to air, water and soil. Usually, a flow model or chart consistent with the system boundaries established in the goal and scope definition is constructed to show the activities in the system and the input and output flows. Then calculations are carried out to estimate the amount of resources used and pollution emissions in relation to the functional unit.

Life cycle impact assessment (LCIA)

In this phase, the objective is to translate the inventory results obtained from the resources use and emissions in the LCI phase to more relevant information on potential environmental impacts. It involves 2 steps; the first, known as “classification” involves assigning and aggregating inventory results into impact categories while the next step, known as “characterization”, involves the estimation of the magnitude of environmental impacts for each impact category and is calculated by multiplying the inventory mass flows with their respective characterisation factors. Optional steps in LCIA include normalization and weighting. Normalization allows for the characterization results of the process or products being studied to be calculated relative to the actual magnitude of each impact in a given region. In the weighting step, the different environmental impacts are weighted relative to each other by multiplying each indicator by an assigned weighting factor relative to their importance in order to obtain a single impact score.

Life cycle interpretation

The final phase of LCA entails using the findings of the LCI and LCIA on environmental releases and impacts in consistent with the defined goals and objectives to arrive at conclusion, decision-making or recommendations. Other aspects of this phase include the validity and reliability of the resulting information, which is often, assessed using sensitivity and uncertainty analysis amongst others.

3.3 Application of LCA to wastewater treatment

The application of LCA within the field of wastewater treatment goes back to the 1990's and till date over 40 international peer-reviewed journals using various databases, boundary conditions and impact assessment approach for result interpretation have been published (Corominas et.al, 2013). However most of these studies are focussed on municipal wastewater planning (Guest et al., and Larsen et al., 2010) and such LCA models do not apply directly to the management of oil and gas exploration and production wastewater due to varying difference in wastewater composition and design. Nonetheless, there is an increasing interest and opportunities for integrating life-cycle thinking into oil and gas exploration and production waste management with several case studies in the area of environmental effects of drilling on the environment, drill cuttings management, drilling fluids management, site remediation, and greenhouse gases (Elcock, 2007).

3.4 Life cycle impact assessment methods and decision objectives

A key aspect of the life cycle Impact assessment is the development of the impact category indicators by relating an environmental stressor to environmental consequence. Environmental impact category indicators form the basis for attributes for decision analysis using LCA (Pettersen, 2007). LCIA uses environmental mechanism to present impact category indicators at different levels of cause-consequence chain. A number of methods based on environmental mechanisms can be used to translate environmental stressors into indicators up to an intermediate level in the cause-consequence chain which are known as the midpoint indicators such as acidification and ecotoxicity; or extend it to the level of value lost to asses damage to human health and ecosystem impacts in what is known as the endpoint indicators. The midpoint approach presents environmental relevance by qualitative comparison, which on the other hand is already included in the indicator for endpoint approach. Also while the midpoint modelling is more comprehensive and with relatively higher certainty level, the endpoint modelling, which involves an informed weighting across categories, provides indicators that are more understandable and better suited for decision objectives (Bare et al., 2002 CCS).

Historically, decision objectives in the LCA of wastewater treatment focuses on the need to protect human health and surface water which makes the toxicity related impacts leading decision attributes, although considering the long term desire for ecological sustainability, attention is now also shifting to minimizing resource loss, energy and water use and reducing or recycling of nutrients (Corominas, 2013). Toxicity related impact indicators derived at midpoint level for a number of environmental recipients such as aquatic, sediment and soil compartments and at endpoint level for human health are presented in the ReCiPe methodology (Goedkoop et al., 2009). However, only the midpoint indicators were used in this study.

4. EVALUATION OF OFFSHORE DRILLING OPERATION SLOP WATER MANAGEMENT

In this chapter, the goal and scope of the study and functional unit will be presented. The drilling operation scenarios including slop volume estimates generated by each well are described followed by foreground system boundaries of the offshore disposal, offshore and onshore treatment set-ups. Finally, the inventory, impact assessment and mass balance of the system will also be described.

4.1 Goal and scope

The primary goal of this study is to assess the environmental impact of offshore slop water treatment and disposal systems applied for slop water generated in different drilling operations and locations including the effect of slop oil content recycling. The scope of this work covers slop water generation during offshore exploratory and developmental well drilling operations that ends just before the well completion stage and the assessment is based on operations within the NCS but is equally relevant for offshore drilling operations elsewhere.

4.2 Functional unit

The functional unit selected is the drilling of a well, given the information available concerning location, depth, formation data, inclination, rig characteristics, waste reuse and logistic, distance to potential waste treatment sites, and other relevant and available information.

4.3 System description

Slop water generated during any offshore drilling operation can either be handled offshore or onshore or by both. In this section, LCA models are presented for offshore injection disposal, three offshore treatment technological options and onshore treatment. A general model outline for the 3 treatment systems identifying their main foreground processes is presented in figure 4.1 below. Each process has been colour-coded to show the sources of the foreground processes inventory.

The turquoise coloured processes were modelled using foreground data collected by myself and from offshore drilling operation inventories previously modelled by MISA. The amber coloured processes were modelled by reviewing and adding new inventories to those originally developed by Torp (2014) for her thesis project based on data collected by herself from MISA database library. The green-coloured processes were modelled by myself for my pre-thesis project, which was based on the same project.

A description of each systems foreground processes and boundaries were also presented in this section. The processes where also colour-coded to show the sources of inventory as initially presented in figure 4.1. With the exception of the onshore treatment system where the slop water treatment facility was considered, capital goods were not considered in the rest of the treatment systems as past studies indicates that they have less significant impact contribution partly due to their long lifetime and multiple uses.

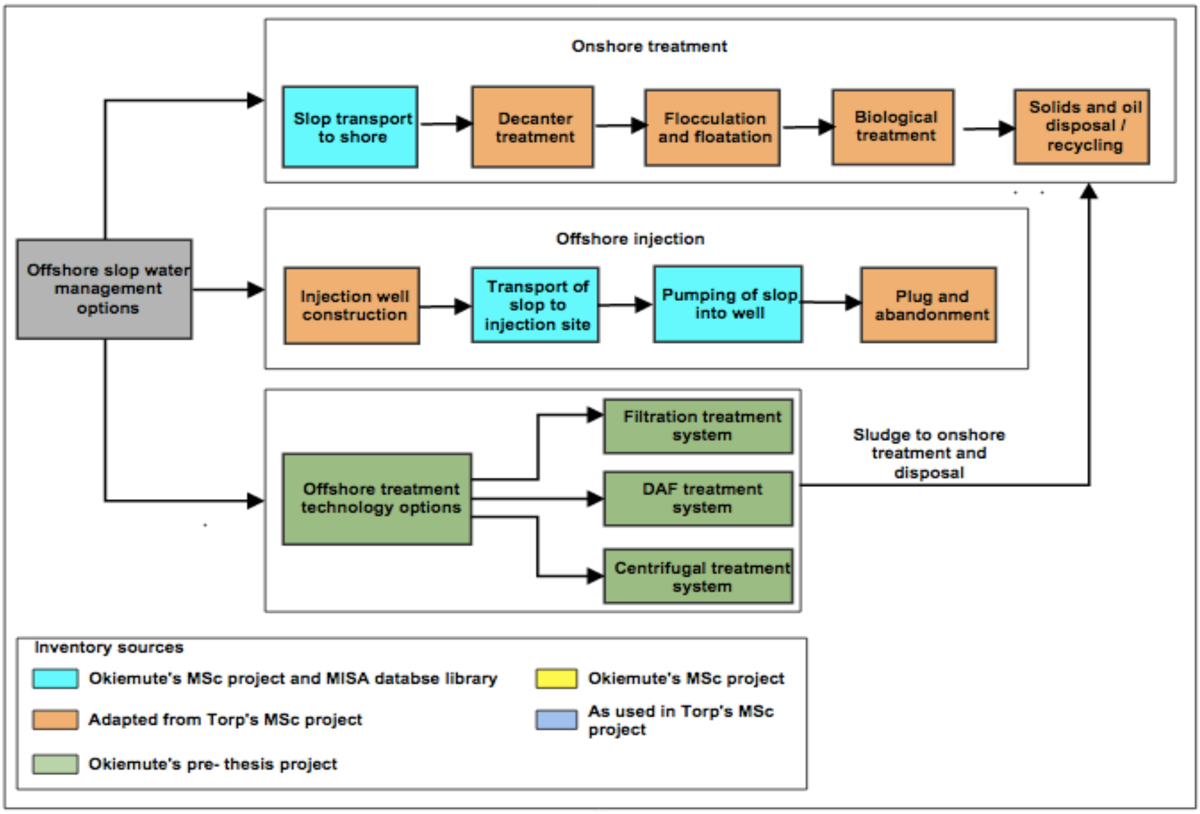


Figure 4.1. Generalised model illustrations of slop water treatment systems

4.3.1 Drilling operations scenarios specifications

The slop water treatment and disposal systems assessment was performed for slop water generated from the drilling of a well in four different offshore drilling operations in the NCS. The well characteristics, drilling fluids used, location are modelled based on example wells drilled in the NCS and the slop water characteristics and volume generated from each well described and estimated. The wells include three exploratory wells and one development well. The exploratory wells are, a hypothetical north sea well, which serves as a baseline well, a deep-water well, and an acrtic region (Barents sea), while the development well is a high-pressure-high-temperature (HPHT) well. Well characteristics data and information were obtained from NPD database and published literature, however with regards to drilling fluids used for the normal, deepwater and HPHT well, it is generally assumed that the upper sections are drilled with WBM and the lower section with OBM with the exception of the arctic well which is only drilled with WBM.

Normal well

This is a hypothetical exploratory well in the Norwegian North Sea, which also served a baseline to which the other well scenarios will be compared with. The well characteristics are summarized below.

Table 4.1. Normal well scenario characteristics

Field name	Hypothetical field in the North Sea		
Wellbore type and name	Exploration		
Water depth	300-350m		
Drilling days	32		
Well length	3500m MD		
Onshore base and distance to field	Florø (150km)		
Nearest onshore treatment facility	Mongstad		
Well sections and drilling fluids used	**Section (inches)**	**Length (m)**	**Drilling fluid type**
	36"	150	WBM
	26"	350	WBM
	17 1/2"	1400	WBM
	12 1/4"	1000	OBM
	8 1/2"	600	OBM
	Total length	3500	

**MD: Measured depth*

Deep-water well

Deep-water wells are wells drilled in water depths ranging from 300m to 1500m, above which they are referred to as "ultra-deepwater wells" (Rocha et al., 2003). The Norwegian Sea deep-water region is situated offshore mid Norway in the northern part of the North Atlantic rift system and between 1997 to 2009 approximately 20-25 exploration wells have been drilled at water depths ranging from 700-1750m with the typical well depth ranging from 3000-5000m RKB depth. Some of the main challenges of drilling operations in this environment are harsh weather, rig storage capacity, logistical challenges arising from relatively long distance of fields

Table 4.2. Deep-water well scenario characteristics

Field name	Aasta Hansteen (Norwegian sea)		
Wellbore type and name	Exploration (6706/12-1)		
Water depth	1262m		
Drilling days	48		
Well length	3910m MD		
Onshore base and distance to field	Sandnesjoen (300km)		
Nearest onshore treatment facility	Sandnesjoen		
Well sections and drilling fluids used	**Section (inches)**	**Length (m)**	**Drilling fluid type**
	36"	1379	WBM
	26"	655	WBM
	12 1/4"	1376	OBM
	8 1/2"	500	OBM
	Total length	3910	

to shore, rig storage ca. The case wellbore described was modelled on an appraisal (exploratory) well at Statoil's Aasta Hansteen field, which was drilled in 2008 and will be the first deepwater well to be produced in the Norwegian Sea commencing from 2017. The field is 300km to land and 140km to the nearest installation (norne). A summary of the well characteristics is presented below.

High Pressure High Temperature (HPHT) well

High-pressure, high-temperature (HPHT) well are defined as wells with wellhead shut-in temperature greater than 690bars and bottom hole static temperature exceeding 150C (Norsok, 2012). In addition to the Norsok definition, the NPD also includes wells that are deeper than 4000m true vertical in its definition of an HPHT well. In addition to their characteristic long depth, HPHT are also commonly located in deep-water regions, and are thereby also faced with challenges of harsh weather, logistics challenges due to long distance of field to shore, rig storage capacity and, all which can have a considerable impact on the volume of slop generated and how they are managed. The HPHT case well used is modelled on Statoil's Kristin field in the Norwegian sea and the characteristics are summarized below.

Table 4.3. HPHT well scenario characteristics

Field name	Kristin (Norwegian sea)		
Wellbore type and name	Development (6706/12-1)		
Water depth	320m		
Drilling days	74-133 (78)		
Well length	5169 MD		
Onshore base and distance to field	Kristiansund (240km)		
Nearest onshore treatment facility	Kristiansund		
Well sections and drilling fluids used	**Section (inches)**	**Length (m)**	**Drilling fluid type**
	36"	92	WBM
	26"	938	WBM
	7 $^{1/2"}$	1288	WBM
	12 $^{1/4"}$	2583	OBM
	8 $^{1/2}$	3950	OBM
	Total length	5169	

Arctic (Barents sea) well

The arctic, which the Barents Sea is part of, is estimated to hold, on a global scale, about 25% of unexploited hydrocarbon resources remaining (DNV, 2013). The Barents Sea is considered to be a sensitive and vulnerable marine environment as a result of its rich concentration of aquatic life and economic value (Vester et al., 2014). In Norway, environmental regulations are generally stricter in the region relative to other parts of the NCS. A zero discharge regime operates in the area, albeit a non-harmful discharge of yellow and green chemicals are permitted. The use of oil-based drilling fluid is also not permitted. The major sources of slop water during exploratory drilling operations are from the deck drainage and possibly from tank cleaning operations where the mud in use contains chemical components that are prohibited from discharge. Other factors that is relevant for slop management includes logistical challenges as current drilling operations are far from shore or any existing offshore support facilities. The case well is modelled after the well described in Paulsen et.al., (2006) and the details are summarized below.

Table 4.4. Barents Sea well scenario characteristics

Well name	Guovca (Barents Sea)		
Wellbore type and name	Exploration		
Water depth	331m		
Drilling days	42		
Well length	1363		
Onshore base and distance to field	Polarbase, Hammerfest (290km)		
Nearest onshore treatment facility	Hammerfest		
Well sections and drilling fluids used	**Section (inches)**	**Length (m)**	**Drilling fluid type**
	36"	48	WBM
	9 $^{7/8"}$	395	WBM
	17 $^{1/2"}$	395	WBM
	8 $^{1/2"}$	525	WBM*
	Total length	1363	

4.3.2 Slop water characteristics and volume

In order to estimate the volume of slop water generated by each well scenario, a generic description of slop water sources, composition, volume estimates was first described and presented in table 4.5. The volumes are theoretical estimates based on information and data gathered from literature and conversation with engineers from oil services/fluid companies and operators. The estimates for each well scenario is presented in table 4.6 and the approach used in reaching the estimates were presented afterwards.

Table 4.5. Slop type, sources, composition and estimated volumes

Slop type (composition)	Source	Estimated volume			Relevant factors	Estimates basis source
		Low	High	Average		
Lightly contaminated slop water (<1% oil, <1% solids)	Deck drainage (contaminated rainwater, melted snow, wash-water and spillages)	4 m3/day	40m3/day	22 m3/day	Use of oil based drilling fluid Drilling duration Weather condition WBM containing red/black chemical components	EPA, 2012, Snaverly and Yarbrough, 1983, Jensen and Toft, 2013, Svensen, 2013 Cupelo et. al., 2014, Massam et. al., 2013.
	Contaminated water phase from tank and pit cleaning water	10 m3 /tank	20 m3 /tank	10 m3 /tank a*	OBM WBM containing red/black chemical components Type of cleaning operation - manual. Automatic/recycling	Hunter et. al., 2014, Massam et al., 2013b, Jensen and Toft, 2013, Svensen, 2013.
	Oil contaminated water interface from displacement seawater/brine	20 m3/well	100m3/well	60 m3/well b*	OBM Length of well and riser Wellbore cleaning efficiency	Herigstad et. al, 2010, SAS, 2008, Mba, 2013, Saasen et al., 2004.
Moderately contaminated slop water (<35% oil, <10% solids)	Oil contaminated wash pills, spacers or brine	20 m3/well	80m3/well	50m3/well	OBM Type and volume of wash pill and spacer sequence.	Herigstad et. al, 2010, SAS, 2008, Irby et al., 2004, Quintero et al., 2008, MI Swaco

Table 4.6. Well scenarios slop water types and volume estimates

Slop type (composition)	Source	Well characteristics and estimated volume (m3/well)			
		Normal well	**Deepwater well**	**HPHT well**	**Arctic well**
		Well type: Exploratory **Drilling fluid: WBM +OBM** **Drilling days: 32** **Well length: 2500m MD**	**Well type: Exploratory** **Drilling fluid: WBM +OBM** **Drilling days: 48** **Well length: 3910m MD**	**Well type: Development** **Drilling fluid: WBM +OBM** **Drilling days: 78** **Well length: 5169m MD**	**Well type: Exploratory** **Drilling fluid: WBM** **Drilling days: 42** **Well length: 1363m MD**
Lightly contaminated slop water (<1% oil, <1% solids)	Contaminated rainwater, melted snow, wash-water and spillages	704	1056	1716	660
	Contaminated water phase from tank and pit cleaning water	10	10	10	_
	Oil contaminated water interface from displacement seawater/brine	60	240	120	_
Moderately high oil-solids contaminated slop (<35% oil, <10% solids)	Oil contaminated wash pills, spacers or brine	50	60	70	_
Well total		824	1366	1916	660

The basis for the estimates used for each scenario is briefly described below.

a. Normal well volumes

i. Contaminated rainwater, melted snow, wash-water and spillages

- Average deck drainage slop volume for a typical well is *22m^3/day* (based on estimated volume outlined in table 4.5*)*, hence a drilling duration of 32 days will generate 704 *m^3/well.*

ii. Tank/pit cleaning water

- Assumed that mud pit tank is cleaned manually once and generated 10m^3 of oily water and 1m^3 of sediments (based on Hunter et al., 2010 estimate of 10-16 m^3 of waste, and includes 1m^3 sediments per tank).

- If cleaning operation is automatic, it is assumed that a total of 90m^3 of oily water and 1m^3 of sediments will be generated. However, if cleaning operation is automatic with recycling, then only 7m^3 of oily water and 6m^3 of sediments will be generated (based on Massam et al., 2013b).

- It should be noted that the number, tank capacities, and frequency of cleaning operations varies significantly from one operation to another.

iii. Oil contaminated displacement water/brine

- Assumed that an average of 60m^3 of slop water is generated as low oil and solids contaminated seawater/brine circulated behind the wash pills/spacer during mud (OBM) displacement to riser at the end of drilling (based on 60m^3 of slop water when rig to sea bed distance of 350m as outlined in table 4.5).

iv. Oil contaminated pills/spacer

- Assumed that 50 m^3 of contaminated pills/spacers is generated from OBM displacement to riser at the end of drilling (based on estimated volume outlined in table 4.5).

b. Deep-water well volumes

i. Contaminated rainwater, melted snow, wash-water and spillages

- Average deck drainage slop volume for a typical well is *22m^3/day* (based on estimated volume outlined in table 4.5*)*, hence a drilling duration of 48 days will generate 1056 *m^3/well.*

ii. Tank/pit cleaning water

- Assumed that mud pit tank is cleaned manually once and generated 10m^3 of oily water and 1m^3 of sediments (based on Hunter et al., 2010 estimate of 10-16 m^3 of waste, and includes 1m^3 sediments per tank).
- If cleaning operation is automatic, it is assumed that a total of 90m^3 of oily water and 1m^3 of sediments will be generated. However, if cleaning operation is automatic with recycling, then only 7m^3 of oily water and 6m^3 of sediments will be generated (based on Massam et al., 2013b).
- It should be noted that the number, tank capacities, and frequency of cleaning operations varies significantly from one operation to another.

iii. Oil contaminated displacement water/brine

- Assumed that an average of 240m^3 of slop water is generated as low oil and solids contaminated seawater/brine circulated behind the wash pills/spacer during mud (OBM) displacement to riser at the end of drilling (based on 60m^3 of slop water when rig to sea bed distance of 350m as outlined in table 4.5 (long riser counts).

iv. Oil contaminated pills/spacer

- Assumed that 60 m^3 of contaminated pills/spacers is generated from OBM displacement to riser at the end of drilling (based on estimated volume outlined in table 4.5). This is 20% higher than normal well considering that the well is about 50% longer and likely to pick up slightly more fluid.

d. HPHT well volumes

i. Contaminated rainwater, melted snow, wash-water and spillages

- Average deck drainage slop volume for a typical well is *22m^3/day* (based on estimated volume outlined in table 4.5*)*, hence a drilling duration of 78 days will generate 1716 *m^3/well.*

ii. Tank/pit cleaning water

- Assumed that mud pit tank is cleaned manually once and generated 10m^3 of oily water and 1m^3 of sediments (based on Hunter et al., 2010 estimate of 10-16 m^3 of waste, and includes 1m^3 sediments per tank).

- If cleaning operation is automatic, it is assumed that a total of $90m^3$ of oily water and $1m^3$ of sediments will be generated. However, if cleaning operation is automatic with recycling, then only $7m^3$ of oily water and $6m^3$ of sediments will be generated (based on Massam et al., 2013b).

- It should be noted that the number, tank capacities, and frequency of cleaning operations varies significantly from one operation to another.

iii. Oil contaminated displacement water/brine

- Assumed that an average of $120m^3$ of slop water is generated as low oil and solids contaminated seawater/brine circulated behind the wash pills/spacer during direct mud (OBM) displacement to riser at the end of drilling. Though water depth is similar to that of a normal well at 320m, the well length is about twice that of normal well, hence the well is assumed to generate $120m^3$ based on $60m^3$ estimate for a normal well as outlined in table 4.5.

iv. Oil contaminated pills/spacer

- Assumed that 70 m^3 of contaminated pills/spacers is generated from OBM displacement to riser at the end of drilling (based on estimated volume outlined in table 4.5). This is 40% higher than normal well considering that well is about 100% longer and a slightly higher quantity of spacer is used and more fluid is picked up.

c. Arctic well volumes

- Volume of slop water generated is based on the actual value provided in Paulsen, et. al., (2005). Besides a mention of wastewater from the drain systems being routed to a dedicated tank, no further indication was given on other sources of slop water generated.

- Only WBM was used in drilling all the sections of the well and all the drilling waste used generated from drilling the upper sections were allowed for discharge. However, KCL/Pac/Glycol fluid used for the 8 ½ contains chloride component, which is prohibited from discharged in the arctic.

- According to the study, a total of 880 m^3 of slop water was generated out of which $660m^3$ was treated and 646.5 m^3 was discharged offshore. While the remaining 220 m^3 were considered to have very high concentration of polymer and unsuited for treatment offshore and thereby sent to shore.

4.3.3 Offshore injection disposal system

The offshore injection disposal system involves the construction of an injection well from an existing offshore platform in a different location from where the slop is generated. The slop, which is commonly mixed with drilling cuttings to make slurry, is transported to the injection site by a supply vessel where it is commonly pumped into the well. When the well capacity is reached, it is plugged and abandoned. A generalised flowchart of the foreground system and inputs presented below in figure 4.1.

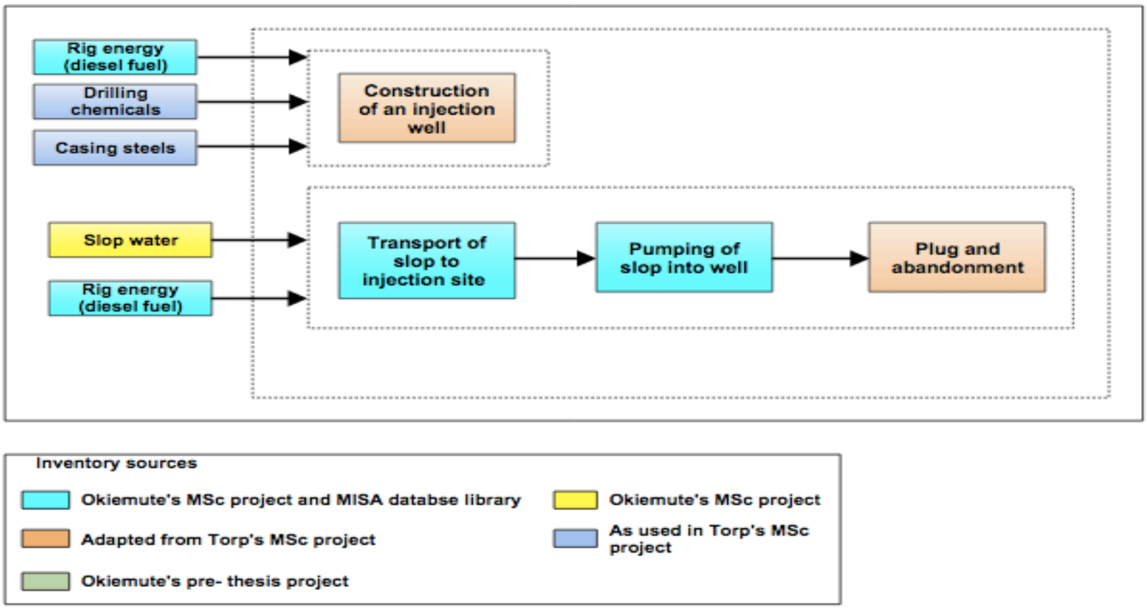


Figure 4.2. Flowchart of foreground system boundary for offshore injection system

4.3.4 Offshore treatment systems

The offshore treatment system includes three technological options that can be applied for the treatment of different types of slop water. These are the filtration based treatment technology used only for the treatment lightly contaminated slop water, the DAF and centrifuge based treatment technologies used for the treatment of both lightly and moderately contaminated slop.

The filtration system removes oil and solids present in slop water using filter cartridges, which are sent to shore for disposal. The filter media of the cartridges is assumed to be mainly composed of polypropylene. A generalised flowchart of the foreground system and inputs presented below in figure 4.2.

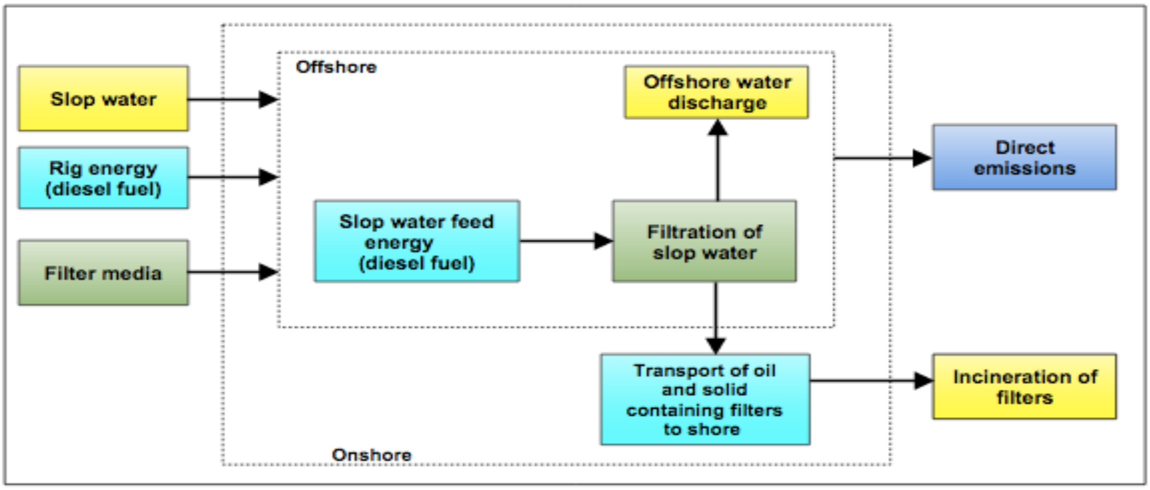


Figure 4.2. Flowchart of foreground system boundary for offshore filtration treatment system

The DAF system discharges treated water offshore and the sludge generated is sent onshore for further treatment to recover or dispose the oil content of slop water while solids are disposed in landfills. A generalised flowchart of the foreground system presented below in figure 4.3.

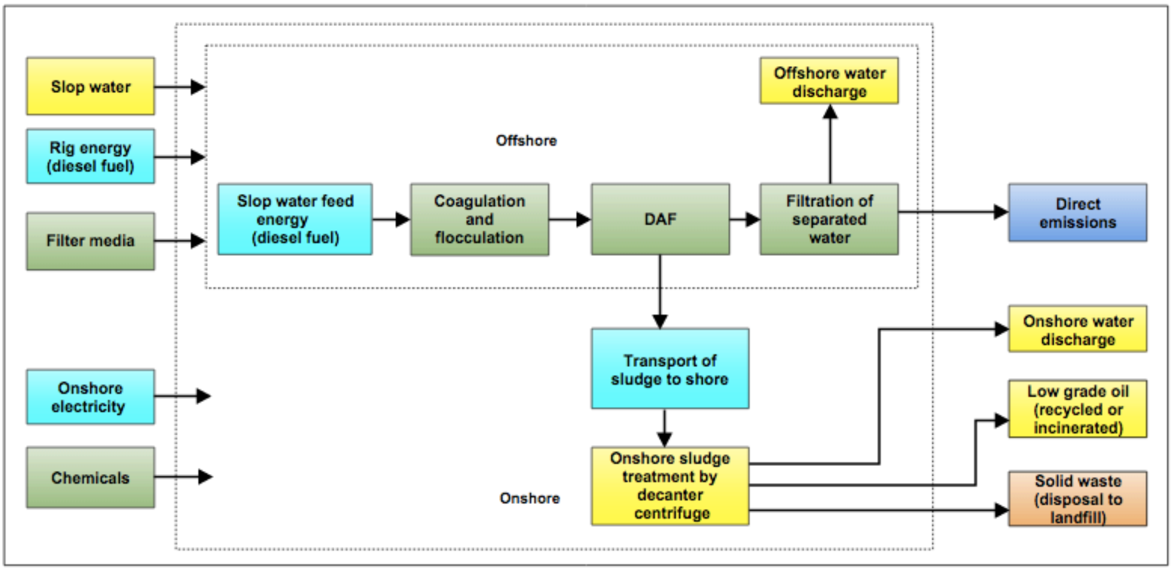


Figure 4.3. Flowchart of foreground system boundary for offshore DAF treatment system

The centrifuge system used for the treatment of lightly contaminated slop water only requires a 3-phase decanting centrifuge which is capable of separating slop into water, oil and solids offshore. The water is discharged offshore and separated oil and solids are sent to shore where oil is either reused or disposed and solids sent to landfill. The centrifuge system used for the treatment of moderately contaminated slop water is similar to the one described above but includes a 2 phase decanter centrifuge for the removal of coarse and heavy solids from slop water in addition to the disc stack centrifuge. A generalised flowchart of the foreground system and inputs presented below in figure 4.4.

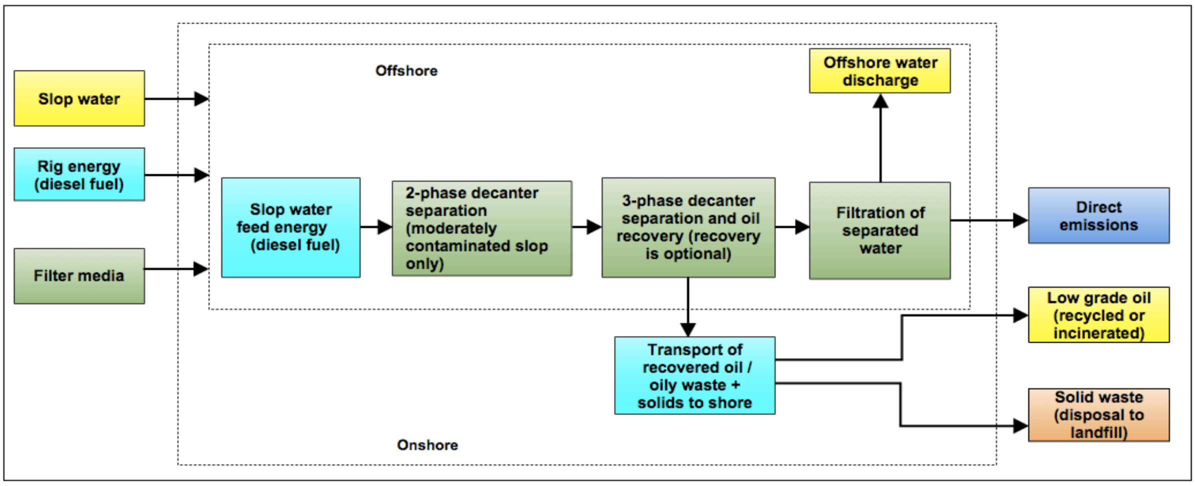


Figure 4.4. Flowchart of foreground system boundary for offshore centrifuge treatment system.

4.3.5 Onshore treatment system

The onshore treatment system was originally modelled by Torp (2014) for her MSc pre-thesis project and is based on Halliburton's drilling waste treatment facility in Mongstad. However, the model was modified for this study mainly in terms of how the content of oil is recovered. In Torp (2014) model, a thermo-mechanical cuttings cleaner (TCC) process was also used to treat slop water sludge leading to the separation of high grade oil as an output but the model in this study does not include a TCC, instead the decanter treatment of sludge produces low grade oil as an output.

When slop water arrives onshore, it is sent to a tank where it is allowed to settle and the water portion is sent to a separate tank for flocculation and flotation treatment. The rest of the water containing most of the solids and oil is sent to 3-phase decanter (similar to the one described in section 4.3.2) where it is separated into more water oil and solids. The water is sent to flocculation and flotation for further treatment while oil is either reuse or disposed and solids sent to landfill. During flocculation and flotation treatment, any settled sludge produced is sent back to the decanter for treatment while the water portion is sent to another tank for biological treatment from where it is discharged. A generalised flowchart of the foreground system and inputs is presented below in figure 4.5

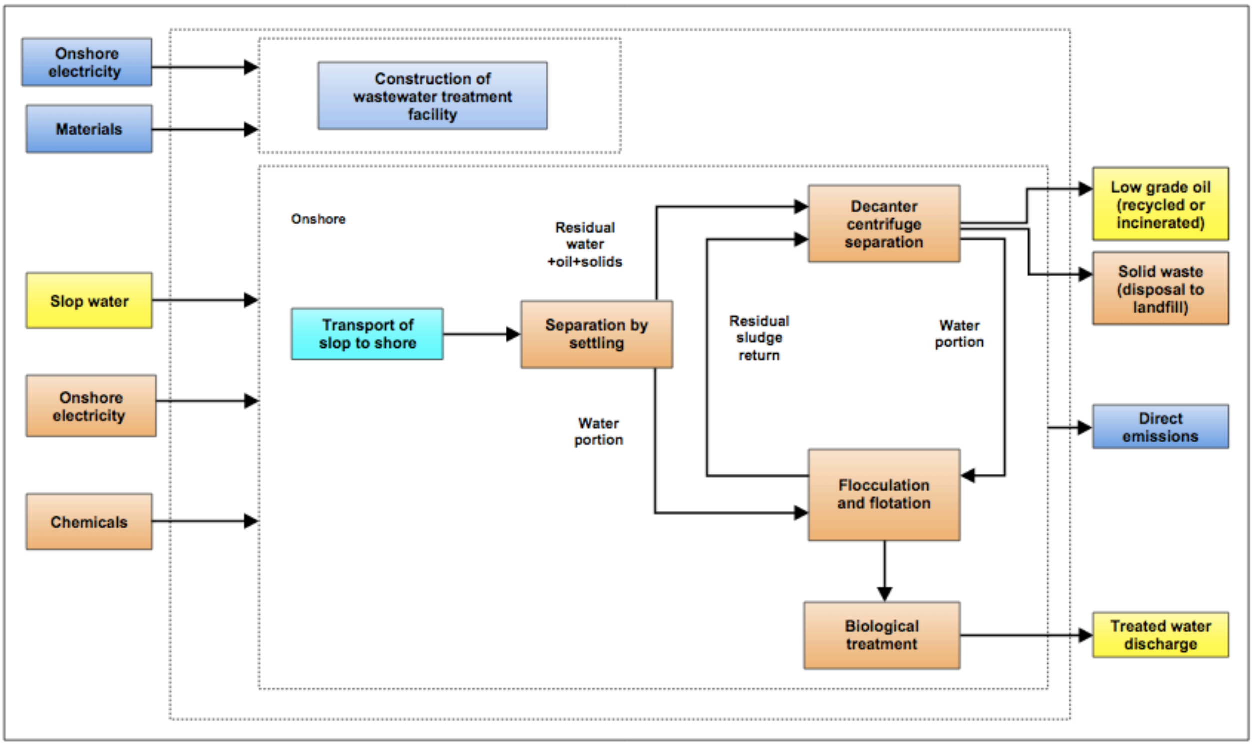


Figure 4.5. Flowchart of foreground system boundary for onshore treatment system

4.3.6 Base oil recovery

Base oil recovery option was described for the DAF, centrifuge and onshore treatment systems. Oil recovery is not a possible option for the filtration and offshore injection systems. It is assumed that emulsion-breaking chemicals were used in conjunction with DAF, centrifuge and onshore treatment systems to aid oil recovery. Emulsion-breaking chemicals are commonly surfactants but within the industry, a complex combination of synthetic polymeric compounds are preferred, which have been difficult to model in this study due lack of information and proprietary nature of these chemicals. However, a water-soluble surfactant known as acrylic acid in the ecoinvent was tested for this purpose in my pre-thesis project but the impact results was insignificant.

For the DAF system, it is assumed that oil and solids present in slop water were removed offshore as sludge during the coagulation and flocculation process and the sludge was sent to shore where it is further processed using the decanting centrifuge during which oil can either be removed or disposed. For the centrifuge system, the centrifuges are located offshore hence oil recovery will also take place offshore but will still have to be sent onshore where it can be reused. But if oil is not recovered, treated water will be discharged and the remaining oily waste will be sent to shore for disposal. For the onshore treatment system, oil recovery is achieved using the decanting centrifuge. The oil recovered by the three systems is assumed to be low-grade oil with quality good enough for return to the crude oil side of the refinery (Hiller-US.com, 2015).

4.4 Impact categories

The Life Cycle Impact Assessment was conducted using the ReCiPe characterisation method at the midpoint level and the hierarchist perspective. ReCiPe is the most recent impact assessment methodology and harmonizes the CML midpoint indicators with Eco-indicator endpoint indicators resulting in eighteen impact categories at midpoint level and three impact category at endpoint level (Goedkoep, 2013). However, only ten out of the eighteen midpoint indicators with the highest values and relevance to the focus of this work are reported. These indicators are presented below:

1. Climate change (CC)
2. Fossil depletion (FD)
3. Human toxicity (HT)
4. Terrestrial acidification (TA)
5. Freshwater ecotoxicity (FET)
6. Marine ecotoxicity (MET)
7. Marine eutrophication (ME)
8. Terrestrial ecotoxicity (TET)
9. Freshwater eutrophication (FE)
10. Ozone depletion (OD)

The assessment was performed based on the ISO 14040 series of standard using SimaPro 7 LCA software. SImaPro comes with several emission databases and impact assessment methods including the Ecoinvent database and ReCiPe impact assessment method, which were both used in this study (Pre Consultants BV, 2007).

4.5 Allocation methods

Allocation refers to the practice of assigning environmental impacts between products produced by a process with multiple outputs, (ISO, 2006). In this study, allocation by weight is applied for all processes. This means that in case of a process involving multiple products or inputs, the environmental impact is simply scaled according to the relative mass of each product input or output.

4.6 Inventory assessment

As earlier pointed out in section 4.3, the inventories used are from five main sources, which are my pre-thesis project carried out in 2013, Anne-Lise Torp's MSc thesis, foreground data collected during the course of this study, MISA offshore drilling inventory and Ecoinvent database.

The offshore injection system and onshore treatment systems were based on inventories initially used in Anne-Lise Torp's MSc work, however some of the inventories were reviewed and new ones added in this work. The offshore treatment systems were based mainly on my pre-thesis project albeit with some reviews for this study. The foreground inventory data used were compiled from relevant literature, manufacturer/products specifications; estimates based on conversation with operators, fluid suppliers and oil services employees. Background data on chemicals and electricity are from the Ecoinvent database and MISA offshore drilling inventory. A complete inventory list is presented in the appendix A, however changes made to the inventories used in Torp (2014) and the newly added ones in this study are briefly explained below.

4.6.1 Offshore injection system inventory

Injection well construction

The construction of an injection well inventory model used in Torp (2014) was based on a study by Sassen et al., (2014). The case well described by Sassen et al., (2014) is located at Utsirahøgda in the NCS and is assumed to hold slurrified drilling cuttings volume of 43573 m3. Torp (2014) assumed that the well was drilled using a floating semi-submersible rig, which required a high amount of fuel for maintaining position and support. However, for this study, it was assumed that the rig used for drilling was a permanent rig already being used for production and as such, the energy consumption is considered to be limited to the derrick and rotary drill operations only. Hence the process used by Torp (2014), named "Drilling Rig, drilling operations, dynamic positioning" was changed to "Drilling operations, on production site (only derrick and rotary)", both modelled by MISA.

Transport of slop to injection site

In Torp (2014) work, the well source or location of the injected slop water was not considered; hence there were no inputs on transport to the injection well site. In this study, it is assumed for all four well scenarios that the slop water source well is located 140km away from the nearest existing field where the injection well is located. The process input used for this was modelled by MISA and named “Supply boat, transport (includes standby time)”. It is a round trip process built on fuel use per hour based on Heidrun rig, which is assumed to be 260 km from Vestbase in Kristiansund and sailing speed of 11.5kn, which corresponds, to 12hours sailing time. The efficiency is assumed to be around 50%.

Energy used for slop injection

In Anne-Lise’s work, the “energy used for slop injection” was modelled using the Ecoinvent process “Diesel, burned in electric-diesel generating set {GLO}|market for|Alloc Def.U»” which is assumed to have a 100% efficiency. But in this study, a similar but modified process modelled by MISA that assumed a 28% efficiency for rig energy derived from diesel fuel electric-generating set was used instead.

4.6.2 Onshore treatment system inventory

The onshore treatment system inventory is also adapted from the one used in the work by Torp (2014) which she modelled based on the Halliburton’s treatment facility in Mongstad. In this study, it is assumed that the onshore treatment system model is the same for all the well scenarios. The only difference is that for each well scenario, the treatment facility is assumed to be located in close proximity to the onshore base where the slop is delivered, hence there is no need to transport slop from base to treatment site, which was included in Torp (2014) study. Some of the new and reviewed inventories used in this study are briefly described below.

Oily waste recycling and disposal

In Torp (2014), the outputs of the onshore decanter include water, low-grade oil and sludge. Whilst the separated water is processed further prior to discharge, she assumed that the low-grade oil is disposed off and modelled the disposal with the Ecoinvent process “Disposal, used mineral oil, 10% water, to hazardous waste incineration/CH U”. The sludge was sent to a TCC where the outputs include recovered high quality oil, which was modelled with the Ecoinvent process “Light fuel oil, at refinery/RER U” and solids which is disposed off in a landfill and modelled with the Ecoinvent process “Disposal, inert waste, 5%, to inert material landfill/CH U”

In this study, the onshore decanter is similarly a 3-phase decanting centrifuge modelled based on manufacturer’s product specification (Hiller-us.com, 2015) whose are also outputs include water, low grade oil and solids. However, in this study the low-grade oil was modelled for recycling and disposal while the water is further processed prior to disposal and the solids is disposed off in a landfill using the same process as Torp (2014) above. The low grade oil recycling was modelled using the Ecoinvent process “Crude oil, at production offshore/NO U” and when it is not recovered, the disposal was modelled with the Ecoivent process "Disposal, hazardous waste, 25% water, to hazardous waste incineration/ CH U". TCC was not included in the model for this study, as it is primarily used for the treatment of drilling cuttings and unsuitable for slop water treatment assessment.

Flocculation and flotation

In the flocculation process modelled by Torp (2014), the dosing concentration of Iron (III) chloride per cubic meters of slop water was 14.55kg/m3, which was considered to be significantly higher than what is reported in published literature. Based on studies on oily wastewater treatment carried out by Pusharev et al., (1983) and Hussein et al., (2014), the optimal dosing concentration for Iron (III) chloride was 1.0 kg/m3, which was used in this study. Also, based on the optimal concentration reported in same studies the dosing concentration for the acid (hydrochloric acid in this case) added alongside Iron (III) chloride was changed from 0.0999kg/m3 reported in Torp (2014) to 0.3kg/m3 in this study.

Biological treatment

In the biological treatment process, the dosing concentration of the de-foaming agent "Struktol SB 20800" reported in Torp (2014) was 0.15kg/m3. The agent was modelled based on the information contained in the chemical data sheet which showed that it contains derivatives of natural fatty acids and fatty alcohol. In this study, the same processes were used but the dosing concentration was changed to 0.004kg/m3 based on the recommended guideline concentration reported for similar agent by its manufacturer (Ferrosorp, 2015).

Transport of slop to onshore facility

The transport of slop to shore process in Torp (2014), was modelled for cranes electricity consumption used offshore and onshore during slop water loading and unloading, cargo vessels and supply vessels using Ecoinvent processes. The cargo vessels process in Torp (2014) was modelled based on the assumption that following the delivery of slop water to the onshore base, it is then transported by a cargo vessel to Mongstad located about 500km away. As pointed out in the introduction of this section, in this study, the treatment facilities for each well scenario is assumed to be located near the onshore base, hence there was no need for an additional transport process to the treatment facilities. The crane processes where also considered to be irrelevant this study.

Transport of waste to onshore disposal sites

In Torp (2014), the landfill and hazardous waste disposal site where modelled based on the assumption that they are both located only 17km away from the Mongstad treatment facility and transported using the Ecoinvent transport process “Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}|market for| Alloc Def, U”. In this study, it was assumed that though solids were sent to a landfill located over the same distance, the impact contributions of this transport process is most likely to be insignificant, hence it was not included in the model. For hazardous waste disposal, it is assumed in this study that the incineration site is located approximately 500km away from Mongstad, 1000km from kristiansund, 1500km from Sandnesjoen and 2000km from Hammerfest. The transport to this site was modeled using the process “Cargo ship, average NO, travelling” from MISA offshore drilling inventory.

Direct emissions

In Torp (2014) report, the direct emissions to water for the onshore treatment system was calculated as an average of the emissions reported by Mongstad and SAR Tannager treatment facilities over the period of 2011 and 2012. However there was a major error in the calculation, which was corrected before use in this study.

4.6.3 Offshore treatment systems inventory

The inventories for the offshore treatment systems, which include the filtration, DAF, and centrifugal treatment systems were mainly adapted from the inventories modelled for the same systems in my pre-thesis project (Okiemute, 2013). In this study, each of the system included a number of new processes while some of the original processes were also reviewed.

There are a number of the processes that is common to two or all three systems but which only varies in the amount or type of inputs that they were applied to. These processes include slop water feed energy, transport to shore, transport of waste to disposal sites, and direct emissions. Hence the approaches used in modelling these processes will only be described once. The individual systems processes are further described below.

4.6.3.a. Filtration treatment system inventory

This system has five processes which are filtration process for filtration technology, slop water feed, transport of used filters to shore, transport of used filters to disposal site and direct emissions. The main modelling approaches employed and information sources are briefly described below.

Filtration process for filtration technology

The filtration process for filtration technology was originally modelled in my pre-thesis project based on the consumption of filter cartridges containing filter media largely composed of polypropylene for the removal of oil from slop. Hence the process was modelled using the quantity of polypropylene consumed to remove oil per cubic meters of slop water filtered and this was calculated as 0.53kg/m^3.

However, in this study, that amount was doubled based on the assumption that the removal of oil and solids present in slop water will result in more consumption of filter cartridges than initially estimated. More so, the increase was used to account for the disposal of oil collected in the filter media since the disposal of filter media which is modelled using the the Ecoivent process "Disposal, hazardous waste, 25% water, to hazardous waste incineration/ CH U", is the same used for oil disposal throughout the models.

Slop water feed energy

In my pre-thesis project, the rig energy supplying pump used to feed slop water to the filtration unit was modelled using the Ecoinvent process "Diesel, burned in electric-diesel generating set {GLO}|market for|Alloc Def.U»" which is assumed to have a 100% efficiency. But in this study, a similar but modified process modelled by MISA that assumed a 28% efficiency for rig energy derived from diesel fuel electric-generating set was used instead.

Transport of used filters to shore

This transport process is modelled using the same transport process described section 4.5.2 for the transport of slop water to onshore facility. The process is in MISA offshore drilling inventory.

Transport of used filters to disposal site

This transport process is modelled using the same transport process described section 4.5.2 for the transport of waste to onshore disposal sites. The process is in MISA offshore drilling inventory.

Direct emissions

The direct emissions to water process in this study is the same as that modelled in Torp (2014), where she assumed that this is similar to the direct emissions of the onshore treatment system due to lack of data for offshore emissions. Unlike the onshore emissions, the offshore emissions included "BTEX" which may have been removed onshore due to the relatively stricter treatment process.

4.6.3.b. DAF treatment system inventory

This system comprises eight main processes namely slop water feed energy, coagulation and flocculation, DAF, filtration of separated water, transport of sludge and used filters to shore, direct emissions, transport of waste to disposal site and onshore treatment of sludge. Only the main approaches and information sources for onshore treatment of sludge and filtration of separated water are summarized below. Coagulation and flocculation and DAF processes remain the same as that modelled in my pre-thesis project and the remaining processes are common to the filtration treatment system in section 4.5.3.a. where they have already been described.

Onshore treatment of sludge

This process was not included in my pre-thesis project. It describes the onshore treatment of the sludge generated from the coagulation and flocculation process during offshore treatment. It is assumed that a significant percentage of the oil and solids are removed as sludge that is sent onshore. The flows of oil, water and solids are described further in a mass balance later in this study. Once onshore, sludge is handled using the onshore treatment processes as described in section 4.5.2 and the outputs subjected to a similar fate. Hence, the low-grade oil can either be recovered for reuse with a quality equivalent to crude oil or sent for incineration while the solids output are disposed off in a landfill.

Filtration of separated water

The amount of filter media used per cubic meters of water filtered was reduced by 50% relative to the amount used in modelling a similar process in my pre-thesis project. The reduction was based on the consideration that a significant proportion of the oil and solids present in slop water feed were removed during coagulation and flocculation leading to less consumption of filter cartridges used to remove the remaining oil present in water prior to discharge offshore. Besides this difference, the process is the same as that described for the filtration treatment system in filtration treatment system in section 4.5.3.a.

4.6.3.b. Centrifuge treatment system inventory

The centrifuge system comprises 8 processes namely decanter feed pump energy, decanter centrifuge, disc stack feed pump energy, disc stack centrifuge, filtration of separated water, transport of used filters, oil and solids to shore, transport to waste disposal sites and direct emissions.

All the eight processes are included in the system when handling moderately contaminated slop but the decanter feed and decanter centrifuge are excluded from the system when used for the treatment of lightly contaminated waste.

Unlike the DAF system, oil recovery takes place onshore due to the separation of slop water into water, oil and solids by centrifuges. Whilst the water is discharged offshore, the oil and solids are transported to shore where the oil can reused as low grade oil of a quality equivalent to crude oil or disposed via incineration and the solids is disposed off in a landfill.

The centrifuge feed pumps and centrifuge separators are all modelled using the same rig energy described in slop water feed energy in section 4.5.3.a. The filtration of separated water is also modelled similarly as that described in 4.5.3.b. above for the DAF system. The reduction of filter media by half in this case is necessitated by the removal of a greater percentage of oil and solids by the centrifuge separator prior to filtration. Both transport and direct emissions processes are the same as earlier described.

4.6.4 Material flow balance

In order to correctly model the recycling and disposal of oil, solids and water composition of slop, a mass balance was performed to describe their flow when slop water is treated by the DAF, centrifuge and onshore systems. The mass balance does not include the offshore injection disposal and filtration treatment system because they both lack oil recovery option.

Offshore DAF and onshore treatment system mass balance

The mass balance below shows again how the offshore DAF and onshore treatment systems are connected. It is assumed that during coagulation and flocculation treatment, about 90% of the base oil and 95% of the solids are removed as sludge. If slop water is emulsified by invert emulsion drilling fluids, emulsion-breaking chemicals may also be added, although this was not included in the flow. The remaining oil and solids present in the separated water are removed during filtration to ensure that water meets the discharge criteria and the filters are sent to shore for disposal while the water is discharged.

The sludge generated is transported to shore where it is separated into water, low-grade oil and solids by a 3-phase decanter centrifuge. The water is further treated to meet onshore discharge criteria and the oil can be sent to the refinery as part of crude or disposed, while the solids can be disposed off in a landfill.

When slop water is not treated offshore by DAF and sent onshore for treatment, it goes through the same treatment by a 3-phase decanter and produces a similar amount of water, oil and solids output described above. Again, more often than not, an emulsion-breaking chemical is added to the slop water to split invert emulsion fluid from water.

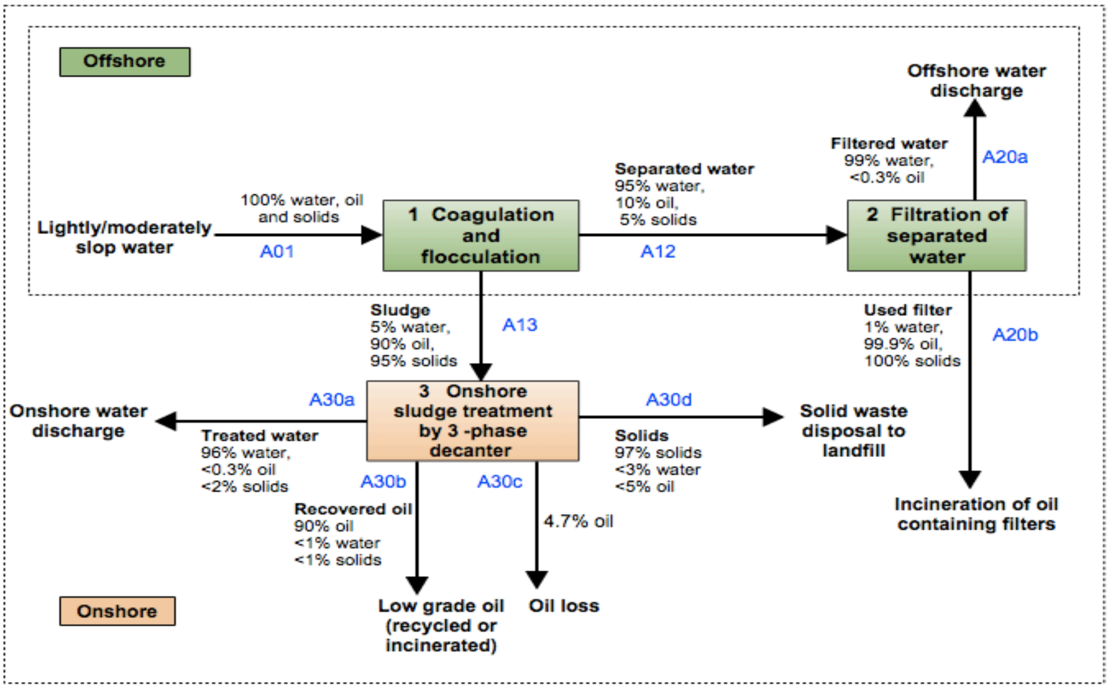


Figure 4.6 A Mass balance illustration for the offshore DAF and onshore treatment system

Offshore centrifuge system mass balance

The 3 phase decanter centrifuge and filtration processes in the centrifuge system mass flow presented in in figure 4.7 are the same as those described for the DAF system in figure 4.6, which means the inputs and outputs are the same. The only difference is that the centrifuge system is a stand-alone system capable of handling the separation of slop water into water, oil and solids onshore. However, the oil and solids do need to be transported onshore for recycling and/or disposal as desired.

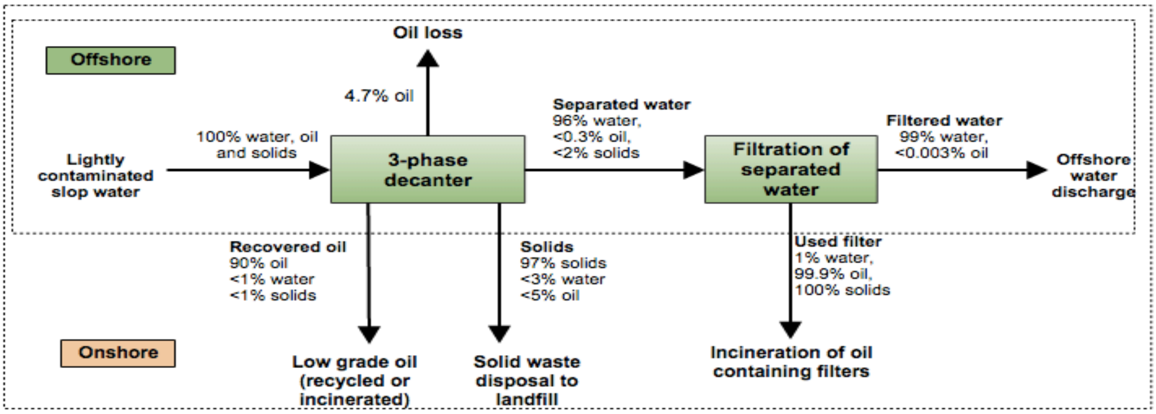


Figure 4.7 A Mass balance illustration for the offshore centrifuge system

It should also be pointed out that, the mass balance described below in figure 4.7 is based on the treatment of lightly contaminated slop only. For moderately contaminated slop, the centrifuge treatment system also includes a 2-phase decanter as described earlier in section 4.5.2, which initially separates slop water into solids and oily water. The oily water can then be treated with a 3-phase decanter as described in the mass balance. This however means that a small portion of the oil is removed with the solids by the 2-phase decanter.

The approaches and sources used as a basis in estimating the material flows described for the systems above are presented in table 4.6 below. The centrifuge treatment system flows in figure 4.7 were not included in the table since these are the same as the flows going in and out of the onshore treatment of sludge by 3-phase decanter and filtration of water processes in figure 4.6 which are already included in the table.

Table 4.6 Slop water material flows approaches

Flows	Flow name	Material	Amount (%)	Source and comment
A01	Slop water feed	Water	100	
		Oil	100	
		Solids	100	
A12	Separated water	Water	95	Based on the average of experimental results published in the following studies: Puszkarewicz (2008), Eckenfelder (1989), Mohammed et al., (2005) Sharaai et al., (2010).
		Oil	10	
		Solids	5	
A20a	Filtered water	Water	99	Mass balance. M I Swaco, 2004, Eia and Hernandez, 2006.
		Oil	<0.3	
		Solids	_	
A20b	Used filter	Water	1	Mass balance. M I Swaco, 2004, Eia and Hernandez, 2006.
		Oil	99	
		Solids	100	
A13	Sludge	Water	5	Mass balance
		Oil	90	
		Solids		
A30a	Onshore water discharge	Water	96	Mass balance
		Oil	<0.3	
		Solids	<2	
A30b	Recovered oil	Water	<1	Flotwegg.com (2015), Hiller-us.com (2015), Quantex.ca (2015
		Oil	90	
		Solids	<1	
A30c	Oil loss	Water	_	Mass balance
		Oil	4.7	
		Solids	_	
A30d	Solids	Water	<3	Mass balance, Flotwegg.com (2015), Hiller-us.com (2015), Quantex.ca (2015).
		Oil	<5	
		Solids	97	

5.0 RESULTS

In this chapter, the results from the life cycle impact assessment will be presented. First, the results for all the treatment systems assessed will be presented for the normal well (baseline scenario) as the environmental load per m^3 of lightly and moderately contaminated slop water treated. The results for the offshore treatment system options that were tested for the lightly and moderately contaminated slop water will also be compared for each of the slop water type but results for the comparison of both offshore and onshore systems will only be presented for the lightly contaminated slop water. This is then followed by the comparison of results for both offshore and onshore treatment systems for the 4 well scenarios presented as the environmental load per total volume of slop water generated by each well. Results for the normal and arctic well scenarios will also be further compared as they both involve the use of different fluid types. All impact results are normalized to the largest impact, which is set equal to 100%.

5.1 Normal well slop water management impact assessment

The results of the impact assessment of the treatment systems applied to slop water generated by normal well, which serves as the baseline scenario are presented in the sections below. Results are shown for each system handling of low and moderately high slop water stream as well as for oil recycling benefits. The results of the treatment systems used for the lightly and moderately contaminated slop water were also separately compared.

5.1.1 Offshore injection disposal system impact

Both low and moderately oil contaminated slop are injected into a dedicated injection well assumed to be located in another existing field 140km away. The result below shows that the energy used for pumping slop into well has the largest contribution in most of the impact categories ranging from about 35% to almost 80% in the CC category. This is followed by the injection well construction process with an average contribution of about 60% to the FET, FE, HT and MET categories.

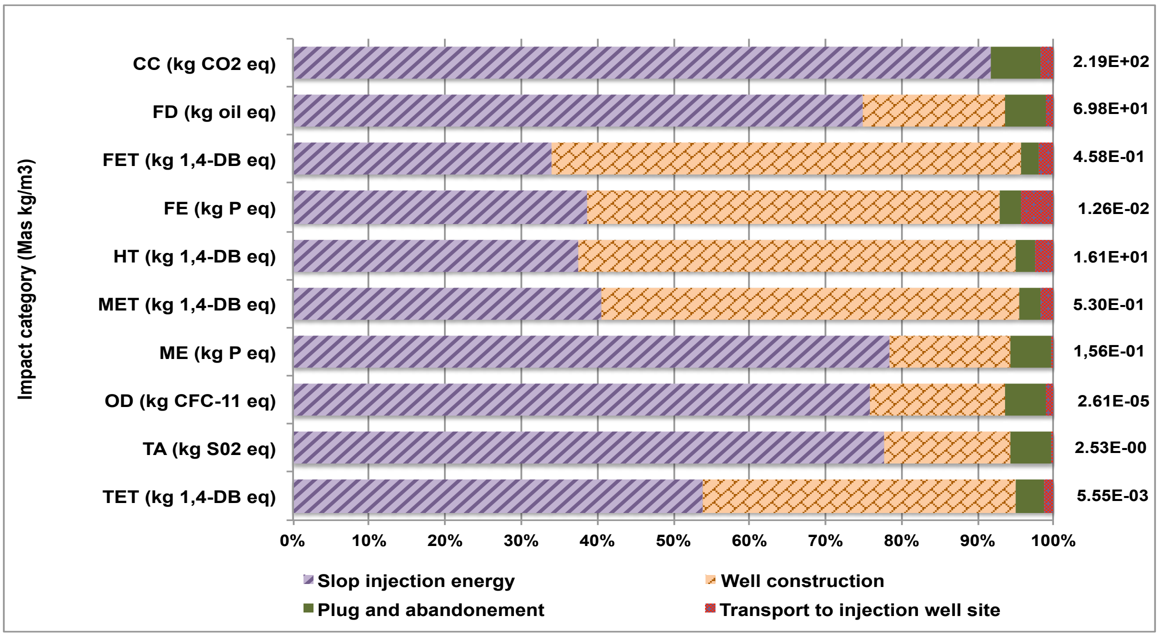


Figure 5.1. Impact assessment of offshore injection disposal of slop water

5.1.2 Offshore treatment systems impact

Results for the offshore treatment systems are presented separately for lightly contaminated and moderately contaminated slop water. The treatment of both the lightly and moderately contaminated slop water by different offshore technology set-ups was assessed. Hence, impact assessment results are presented below for the two treatment technology set-ups used to treat lightly contaminated slop water i.e. filtration and DAF-based technologies and those used to treat the moderately contaminated slop. i.e. DAF and centrifuge based technologies.

5.1.2.1 Lightly contaminated slop water treatment

The filtration and DAF-based technologies are the applicable treatment for lightly contaminated slop water and their results are presented below. For DAF technology, results were presented for the disposal and recycling of oil present in slop water. There is no recycling option for the filtration technology as the filter cartridges remove oil present in slop water.

a. Filtration based treatment system

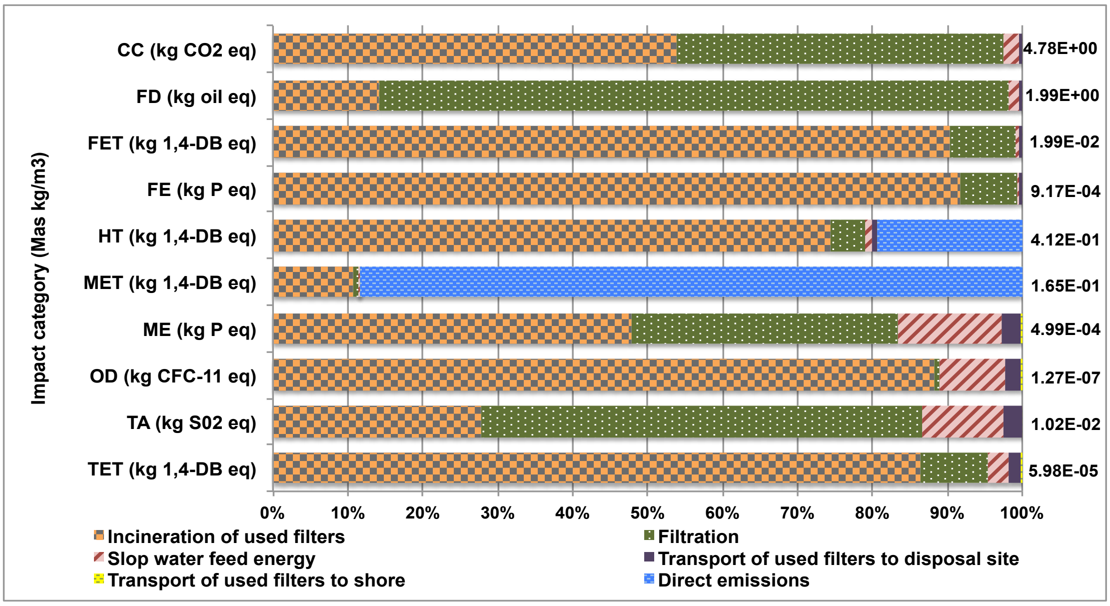


Figure 5.2. Impact assessment of offshore filtration based treatment of lightly contaminated slop water. This technology does not have an oil recovery option.

The filtration based treatment technology is dominated mainly by the incineration of used filters compared to its production and use. The impact is based on a generic hazardous waste incineration process in the ecoinvent database. The filtration process impact is due to the filter media used in the filter catridges (assumed to be mainly composed of polypropylene). The amount of the filter media consumed and incinerated was doubled from what is normally required per m^3 of slop water to on the one hand, account for the extra filter media consumption required to remove oil and solids and on the other hand, account for the disposal of oil removed, which is incinerated together with the filter media. Direct emissions to water dominates the MET category and contributes about 20% to the HT category. This based on a cocktail of heavy metals and pollutants assumed to be present in discharged treated water and are assumed to be similar to those present in discharged water from onshore treatment.

b. Dissolved air flotation (DAF) based treatment system

The dissolved air flotation (DAF) system is significantly dominated by onshore treatment of sludge generated during offshore treatment when oil present in slop water is not recycled as shown in figure 5.3. Contribution analysis of the process shows that the high impact score is mainly due to the disposal of the oily waste separated from the sludge following treatment by the decanter centrifuge onshore. When oil content of slop water is recycled as shown in figure 5.3, there is over 100% reduction in the FD category with an additional benefit of about 64% in avoided impacts and also an average reduction of about 46% in the scores of the rest of the impact categories. Oil is recovered as an output during the treatment of the sludge sent onshore by the decanter and it is assumed to be of a quality good enough for return to the crude oil side of a refinery. The contributions of direct emissions to MET and HT is similar to that of filtration treatment system.

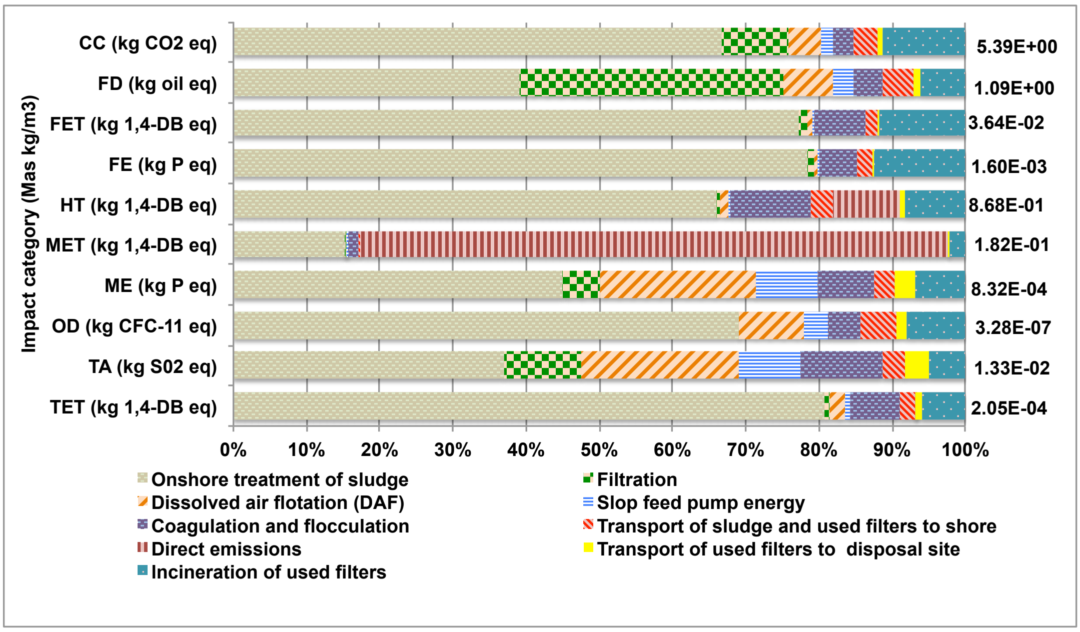


Figure 5.3. Impact assessment of offshore DAF based treatment of lightly contaminated slop water when oil content is disposed without recycling.

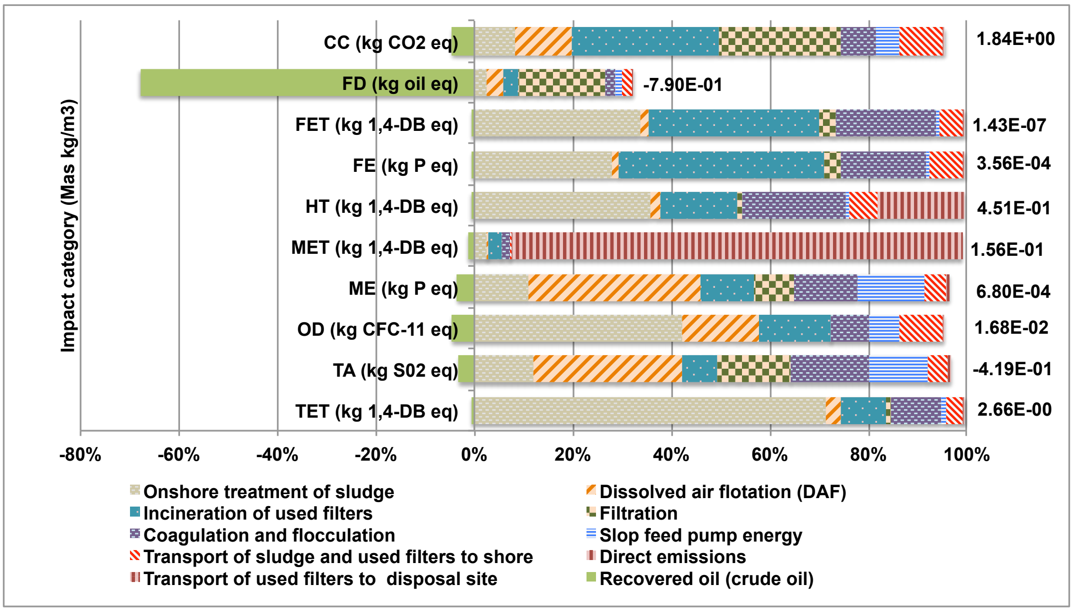


Figure 5.4. Impact assessment of offshore DAF based treatment of lightly contaminated slop water when oil content is recycled.

c. Centrifuge based treatment system

The result presented in figure 5.5 for the centrifuge-based technology when the oil content is disposed via incineration shows that the largest impacts contributors are the incineration of filters and oily waste, and energy use of the disc stack centrifuge. The significance of oil waste disposal is evident in the impact scores of the result presented in figure 5.6 for when oil is recycled, where there is over 100%, 70% and 50% reductions in the FD, FET and CC impact scores respectively and recycling benefits similar to the DAF system. As a result, the impact categories dominance shifts to the disc stack centrifuge energy use, which is from the combustion of diesel in an electricity generating set with an estimated efficiency of about 28%. The direct emissions contributions remain the same as those of the systems presented earlier.

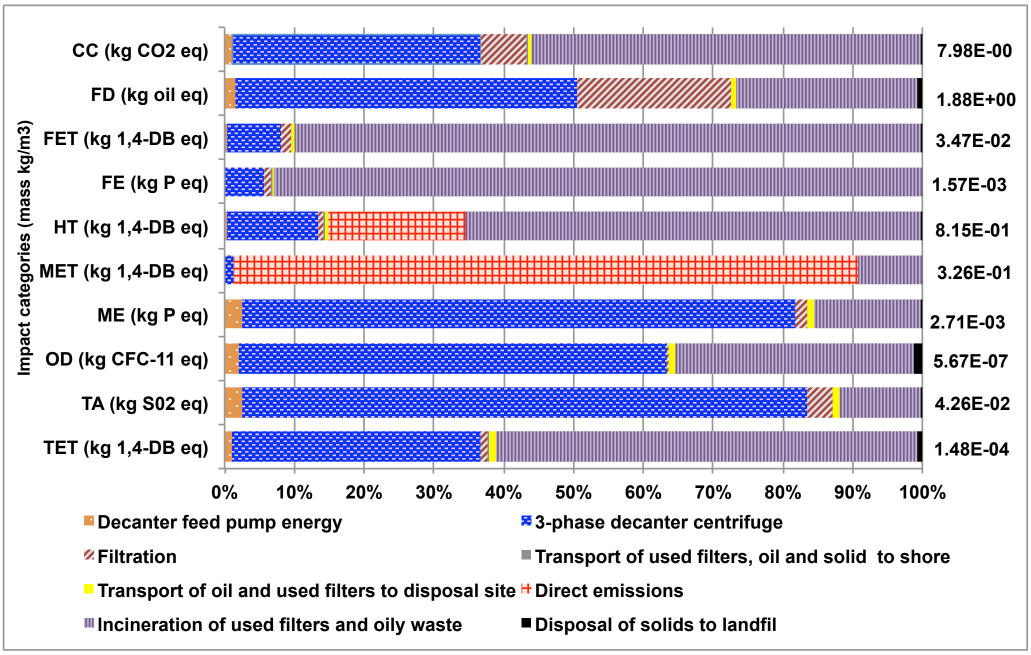


Figure 5.5. Impact assessment of offshore centrifuge based treatment of lightly contaminated slop water when oil content is not recycled.

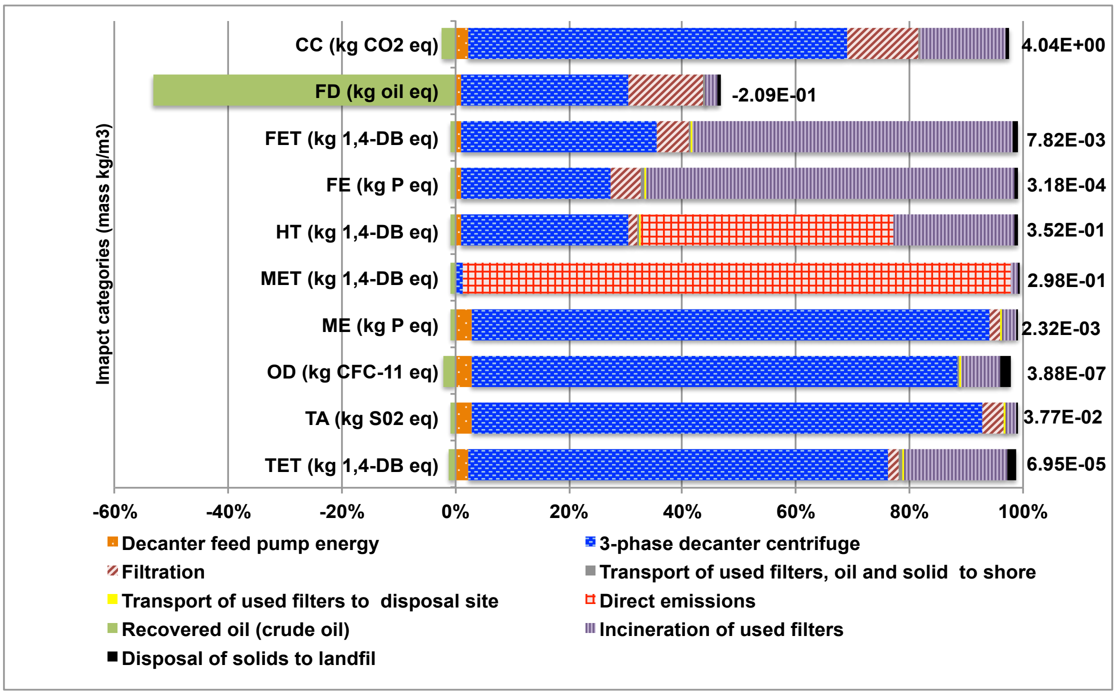


Figure 5.6. Impact assessment of offshore centrifuge based treatment of lightly contaminated slop water when oil content is recycled.

A comparison of the impact assessment of the three systems i.e. DAF, Centrifuge and filtration based systems used offshore for the treatment of lightly contaminated slop water when oil content is disposed and recycled is presented in figure 5.7 below.

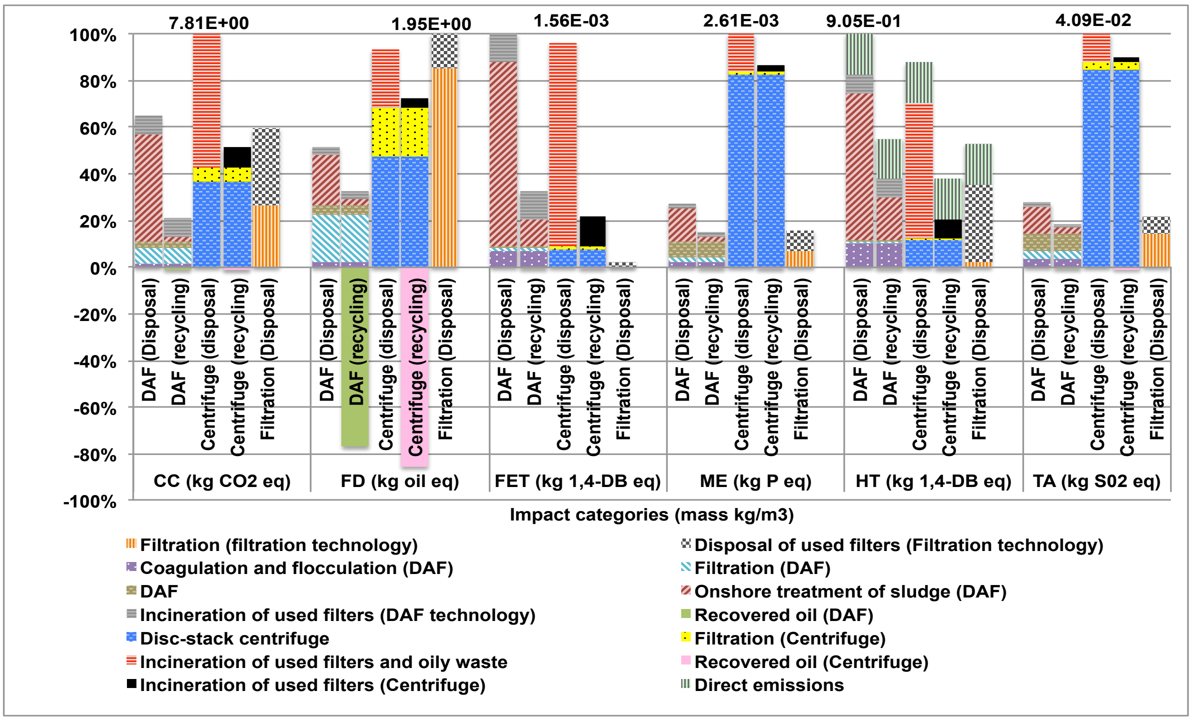


Fig 5.7. Comparative impact assessment of lightly contaminated slop treatment by the filtration and DAF based technology. The DAF and centrifuge based systems comprises results for oil disposal and recycling.

The above comparison shows that the centrifuge-based technology emerges with the highest impact score overall for both oil disposal and recycling scenarios mainly due to disc stack centrifuge energy use which contributes as high as 80% to the ME and TA categories. When oil is not recycled, the DAF system is higher than the filtration system overall mainly due to the oily waste incineration, but when oil is recycled, the DAF system emerges with the lowest score in the CC and FD categories and almost joint lowest with the filtration system in ME, HT and TA categories. Due to the lack of a recycling option for the filtration based system, the disposal of filter containing oil appears to be an important contributor to its impact score and it emerges with the highest impact in the FD category mainly due to polypropylene composition of the filter media.

5.1.2.2 Moderately contaminated slop water treatment

The treatment technologies used for moderately contaminated slop water are the DAF and the centrifuge based treatment systems. The results for both systems showing when oil is disposed and recycled are presented in the sections below.

a. Dissolved air flotation (DAF) based technology system

The result for DAF treatment system scenarios for moderately contaminated slop water presented below is similar to that of the lightly contaminated slop water presented in figure 5.5, except that the impact due to oily waste incineration is much greater due to the higher content of oil in this slop water stream, reaching around 90% in all the impact categories. The moderately contaminated slop water is assumed to contain 40 times more oil per m^3 of slop water relative to the lightly contaminated oil, resulting in a proportional increase in impact. Similarly, when oil is recycled as the result in figure 5.9 shows, there is a proportional decrease in the impact and benefits as seen in the FD category where the benefit is highest and also across the other impact categories.

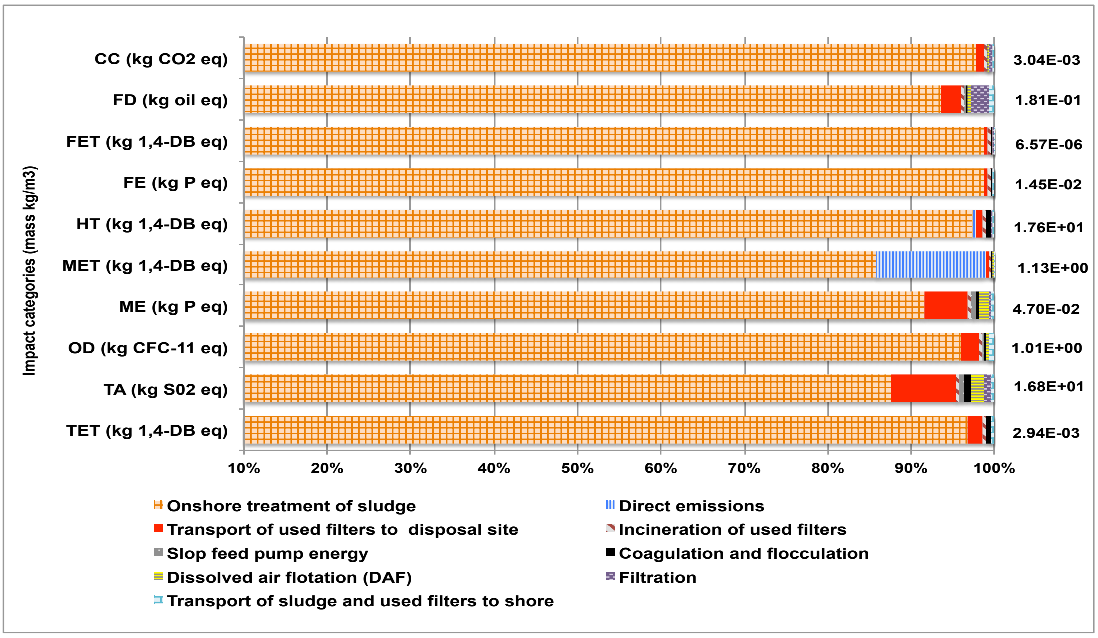


Figure 5.8. Impact assessment of offshore DAF based treatment of moderately contaminated slop water when oil content is disposed without recycling.

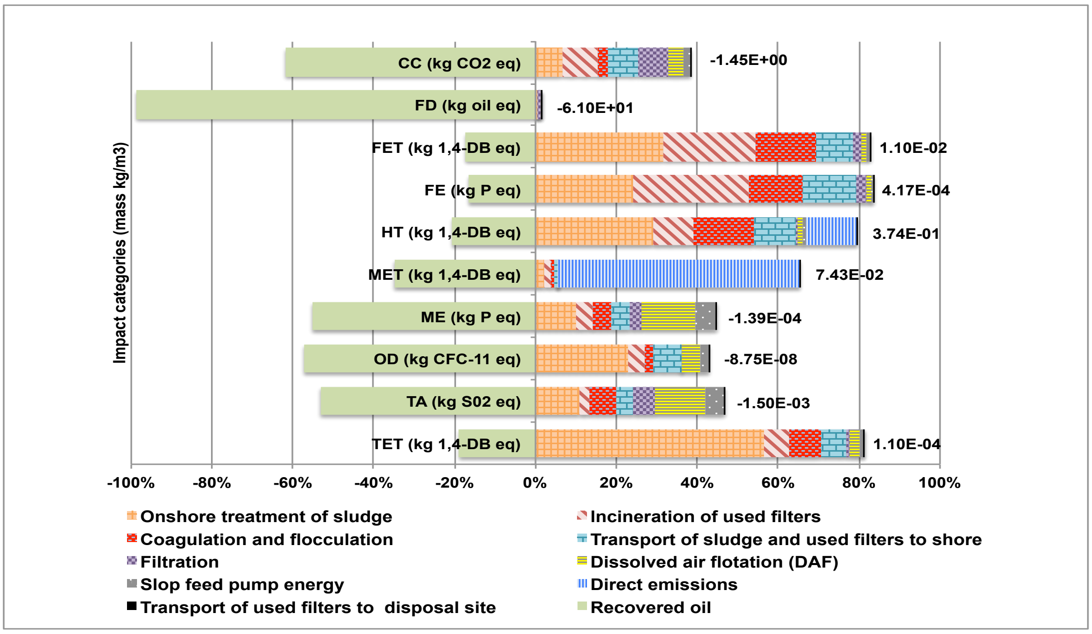


Figure 5.9. Impact assessment of offshore DAF based treatment of moderately contaminated slop water when oil content is recycled.

b. Centrifuge based technology

The results for the treatment of the moderately contaminated slop water with a centrifuge based treatment system is also very similar to that of lightly contaminated slop water but with a proportionally higher impact scores across the categories for both when oil is disposed and recycled due to the higher oil content. However, the system is slightly different from that used for the treatment of lightly contaminated slop as it also includes the additional impact of 2-phase decanter centrifuge process, which is absent in the other system.

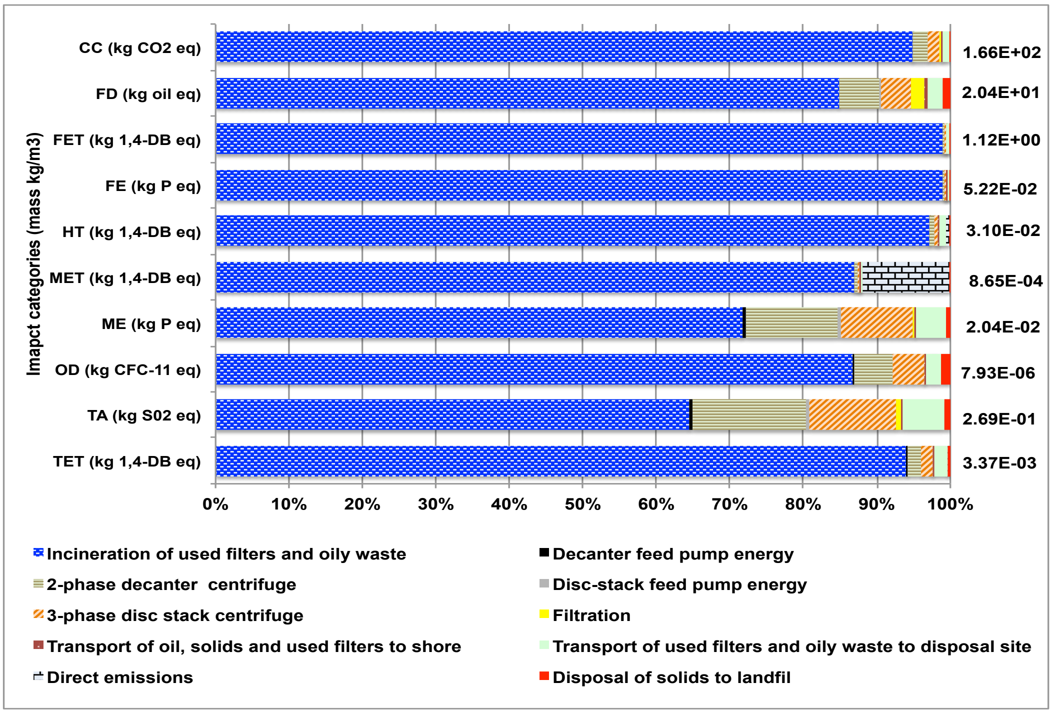


Figure 5.10. Impact assessment of offshore centrifuge based treatment of moderately contaminated slop water when oil content is disposed without recycling.

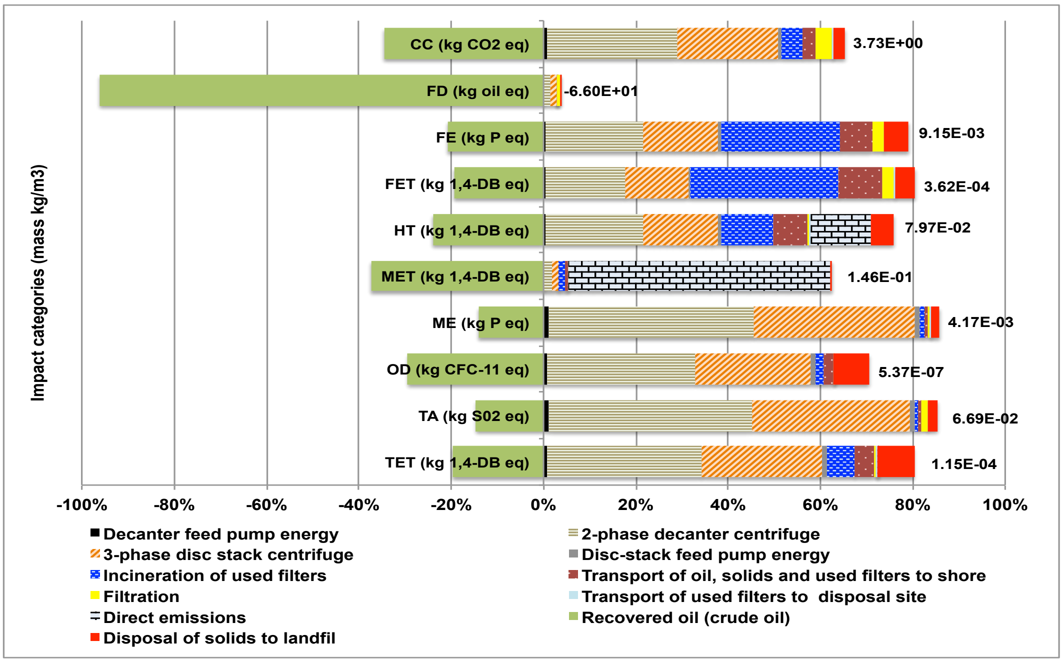


Figure 5.11. Impact assessment of offshore centrifuge based treatment of moderately contaminated slop water when oil content is recycled.

A comparison of the DAF and centrifuge systems used for the treatment of the moderately contaminated slop is presented below in fig 5.12, and shows the overbearing dominance of the oily waste disposal for both systems when oil is not recycled. However, the centrifuge-based technology just emerges with the worse performance than the DAF system with the additional contributions from the energy use of 2 and 3-phase centrifuges. The avoided impact due to oil recycling is slightly higher for the centrifuge-based system relative to the DAF system where a small percentage of the oil is removed during the coagulation and flocculation prior to oil recovery. Overall though, the DAF systems emerges with the lowest impact for both disposal and recycling scenarios when considering the contributions of the 2 and 3 phase centrifuges to the centrifuge system.

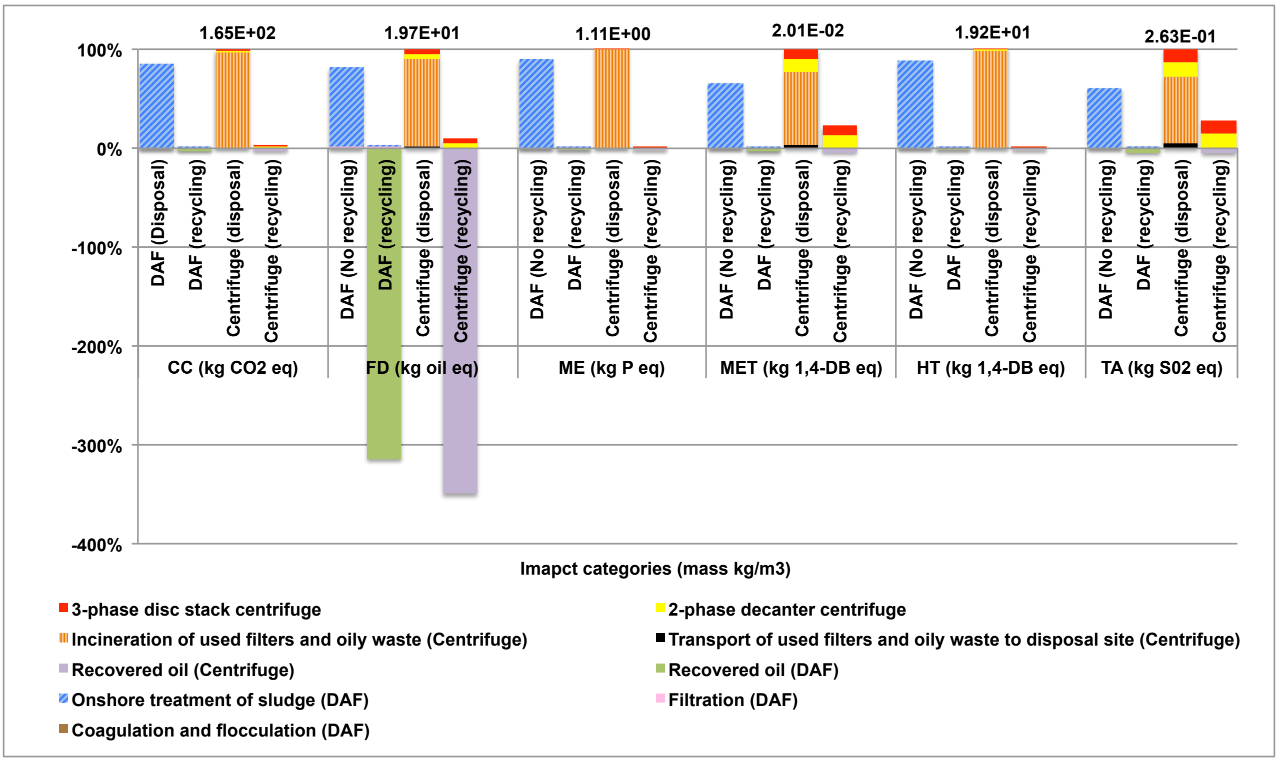


Fig 5.12 Comparative assessment of moderately contaminated slop treatment with the disposal and recycling of oily waste using the DAF and centrifuge based technology.

5.1.3 Offshore and onshore treatment comparative assessment

Figure 5.13 below shows the result for the comparison of the offshore and onshore treatment systems for lightly contaminated slop water. Results for moderately contaminated slop will not be presented, as it is similar to that of lightly contaminated slop water except for the increase in impacts due to oily waste disposal or recycling in proportion to the oil content of slop water. Overall the offshore injection disposal of slop clearly overpowers the rest of the system, which are well below 10% or much less in some cases, except in the FET and HT categories where onshore treatment is slightly above 20% due to contributions from biological and flocculation treatment processes. The offshore injection disposal impact is mainly due to energy use during injection contributing an average of 80% to the scores of CC, FD, ME, TA and an average of 40% to FET and HT categories.

The result for oil recycling was not included in this comparison, as the offshore injection result will remain unchanged due to the lack of recycling option for this system, which also means that the conclusions will remain the same. Instead, a different result comparing offshore and onshore treatment systems for both the disposal and recycling of oily waste but with the exclusion of offshore injection is presented in figure 5.15 and 5.16.

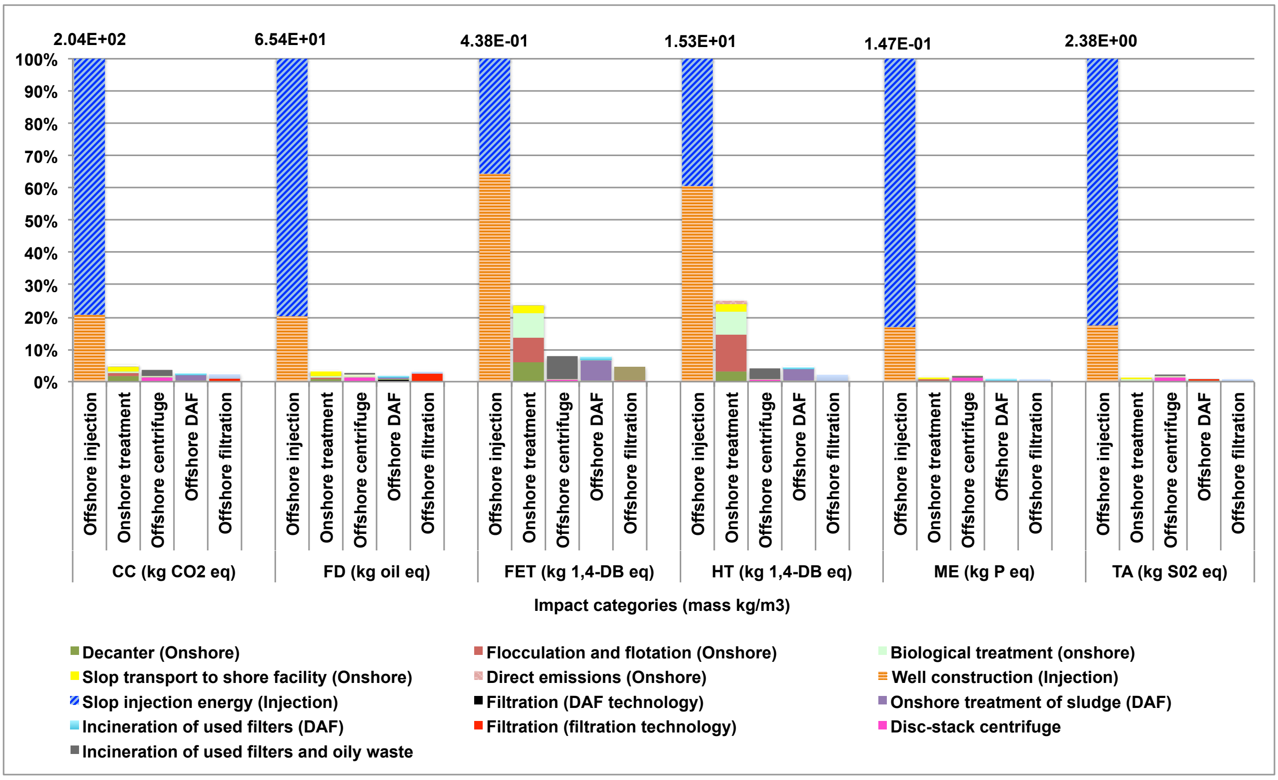


Fig 5.14. Comparative assessment of offshore and onshore treatment/disposal systems

5.1.4 Offshore and onshore treatment systems comparison excluding offshore injection

The comparison of offshore treatment system options (filtration, DAF and centrifuge) and onshore treatment of slop when oil is disposed as presented in figure 5.15 shows that onshore and the centrifuge based treatment systems are the dominating systems with onshore treatment having the highest impact scores in the CC, FD, FET and HT categories and centrifuge based treatment making the highest scores in the ME and TA categories. The main contributors to onshore treatment impact are the decanter (whose impact is also mainly due to oily waste incineration), the transport of slop water to shore (assuming a 50% transport efficiency), biological and flocculation/flotation treatment processes in that order.

The relatively higher scores of the centrifuge based treatment is mainly due to energy use of the disc stack centrifuge, contributing about 80% alone to the ME and TA categories, where the system's impact is highest. The DAF system only slightly edges the filtration system in the FD category and the impact in this category is mainly due to the production of polypropylene content of the filter media. More so, the amount of filter cartridges per m^3 of slop was doubled for the system to account for the extra filter media consumption required to remove oil and solids and the disposal of removed oil that is incincerated with the filter cartridges.

When the oil content of slop water is recycled, the impacts result as presented in figure 5.16 shows a significant reduction in the impact scores of the processes dominated by oily waste disposal in figure 5.15. For instance in the CC category, there was a 99%, 94% and 86% reduction in "decanter" process of onshore treatment, "onshore treatment of sludge" process of the DAF system" and "incineration of filters and oily waste" process of the centrifuge respectively. These reductions also resulted in a 41%, 67% and 50% reduction in the total CC scores for onshore treatment, DAF and centrifuge based systems respectively. A similar trend can also be observed in the other impact categories.

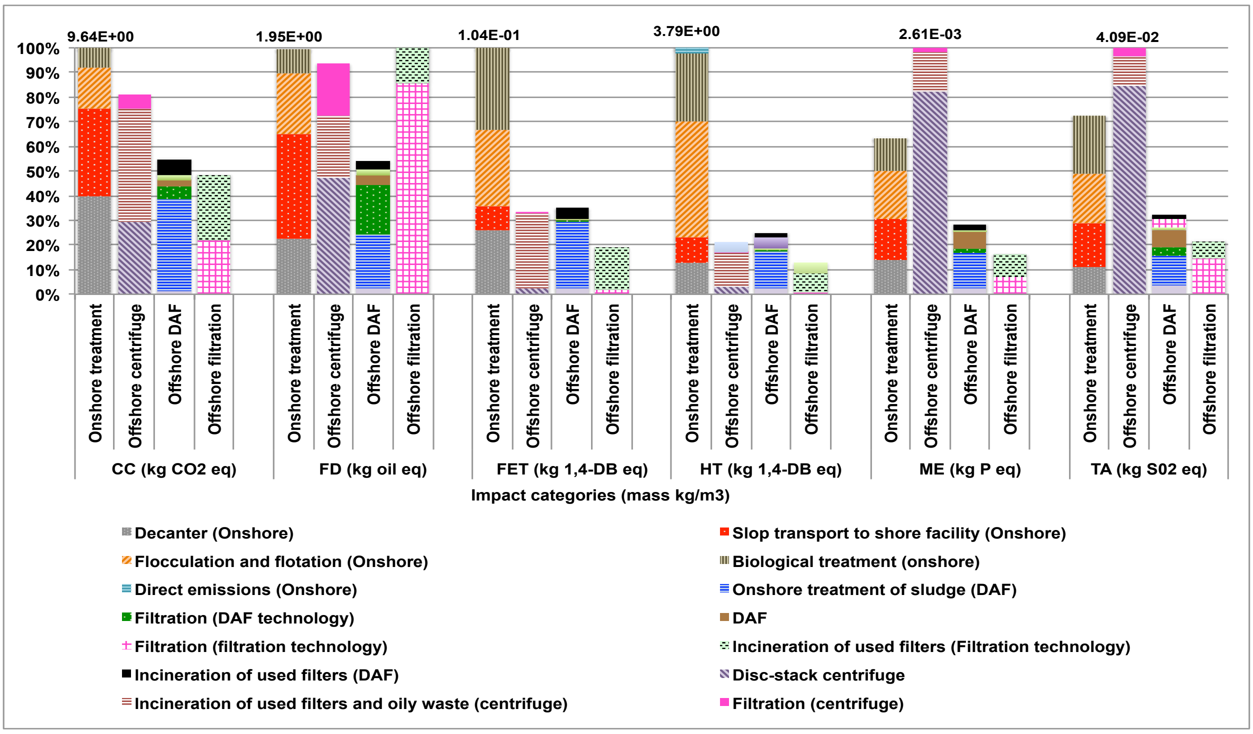


Fig 5.15 Comparative assessment of offshore and onshore treatment technologies without oil recycling (excluding offshore injection)

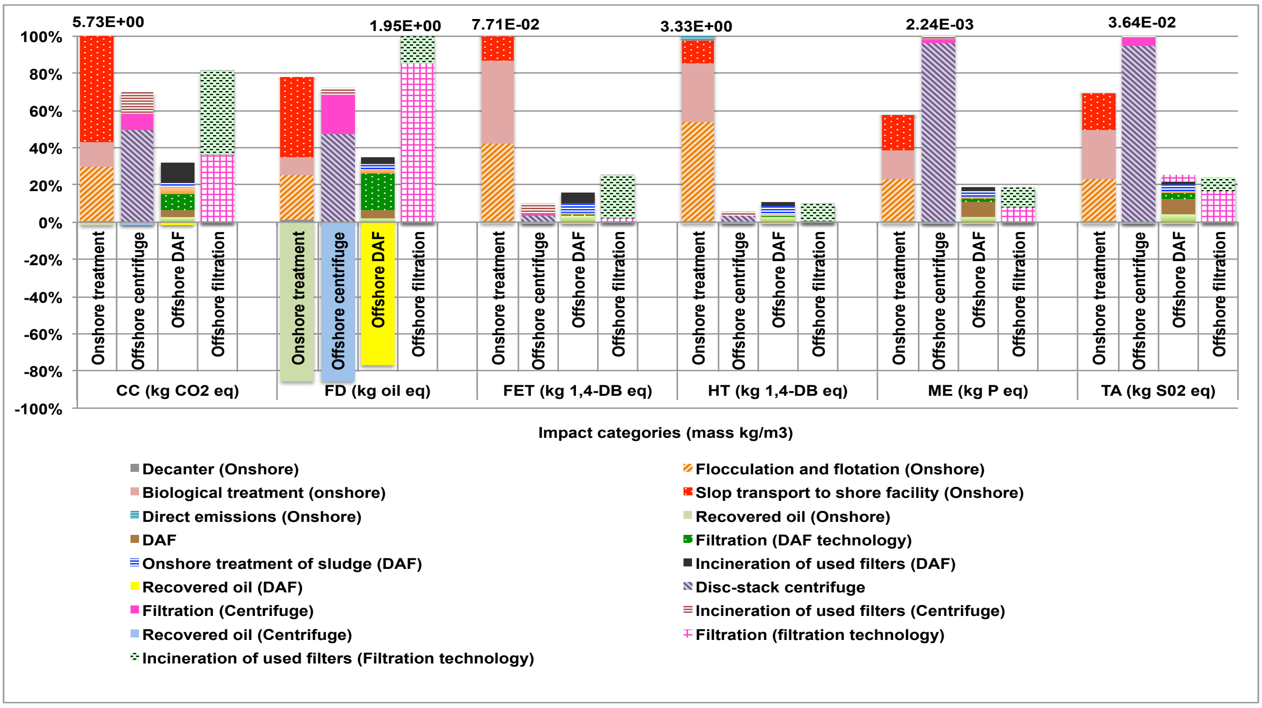


Fig 5.16 Comparative assessment of offshore and onshore treatment technologies with oil recycling (excluding offshore injection)

5.2 Drilling operation scenarios comparative assessment

The offshore and onshore treatment systems were also compared based on the treatment of the total volume of lightly contaminated slop water generated by the normal well and the 3 other well scenarios (i.e. deep-water, HPHT and arctic wells) to highlight the parameters that varies between wells and consequently affects the impact results. Offshore injection was excluded in the comparison, as it is likely to overpower the rest of the system as witnessed earlier in figure 5.14.

The comparison revealed that the variations in the treatment systems impacts results are mainly due to the variations in volumes of slop water generated, logistics to shore and type of drilling fluids used by the respective wells. However, only the onshore treatment system significantly highlights these variations and the results is presented below in figure 5.17 for when oil is disposed and in figure 5.18 for when oil is recycled. The rest of the treatment systems showed a similar trend for the four well scenarios and their results are provided in appendix x.

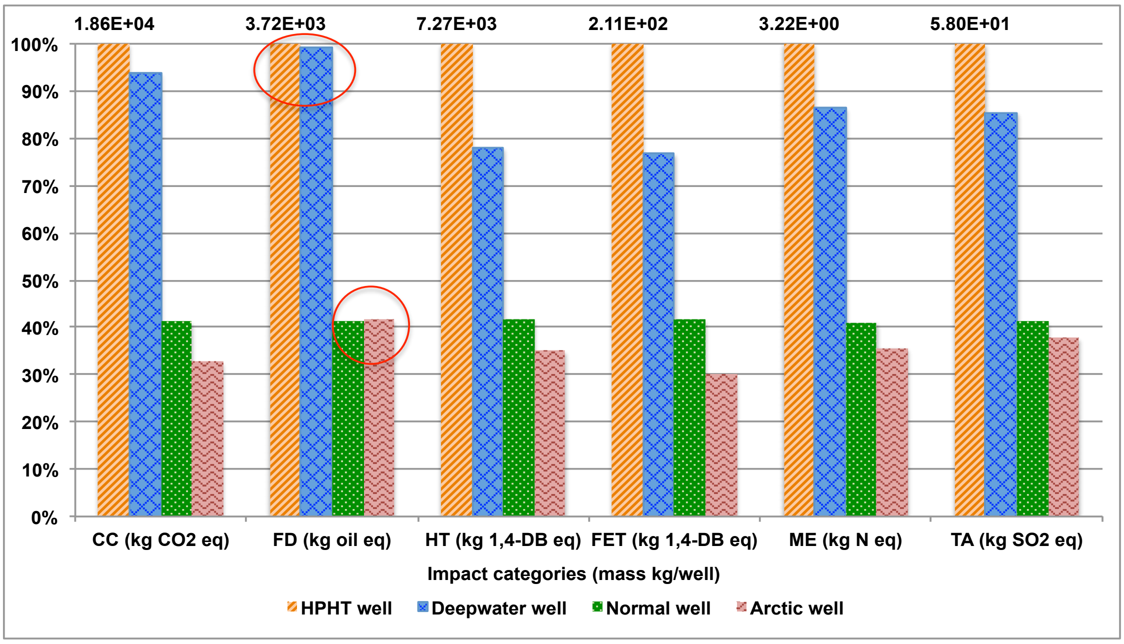


Figure 5.17. Comparison of onshore treatment systems impact assessment for all four well scenarios when oil is disposed

As shown in the figure above, overall, the HPHT well scenario has the highest impact score for all the treatment systems across the impact categories followed by the deep-water, normal and arctic wells, except in the FD category where there is a score parity between HPHT and deep-water wells on one hand and normal well and arctic wells on the other. On a general note, the pattern of the result indicates a relationship between the impact scores and the volume of slop water generated by the individual wells. The estimated volume of lightly contaminated slop water generated by the HPHT, deep-water, normal and arctic wells are 1846 m^3, 1306 m^3, 774 m^3 and 660 m^3 respectively. Hence, it can be seen that the impact scores are proportional to the volume of slop generated by the respective wells.

With regards to the score parity of HPHT and deep-water in the FD category as highlighted in the result (when deep-water should be less due less slop volume relative to HPHT), contribution analysis showed that the additional increase in deep-water well score was due to contributions from the transport of slop to shore, as the deep-water well is the farthest from shore at 300km relative to normal, HPHT and arctic which are 150km, 240km and 290km respectively. For the score parity in normal and arctic well, a detailed results showing the variations in the significant processes and impact scores relative to the normal well scenario is presented in the next section.

In figure 5.18, the recycling of the oil content results in a corresponding reduction in the total scores of each of the system based on their oil content. The biggest benefits can be observed in the FD category for HPHT and normal well. The deep-water well did not show a corresponding benefit especially in the FD and CC categories, again mainly due to the counteracting effect of the impacts contributions from the transport of slop water to shore which is farthest for deep-water well. A similar explanation can also be offered for the arctic well result, which is now slightly above the normal well in the CC, ME and TA categories, however details of arctic well results will be discussed in the next section.

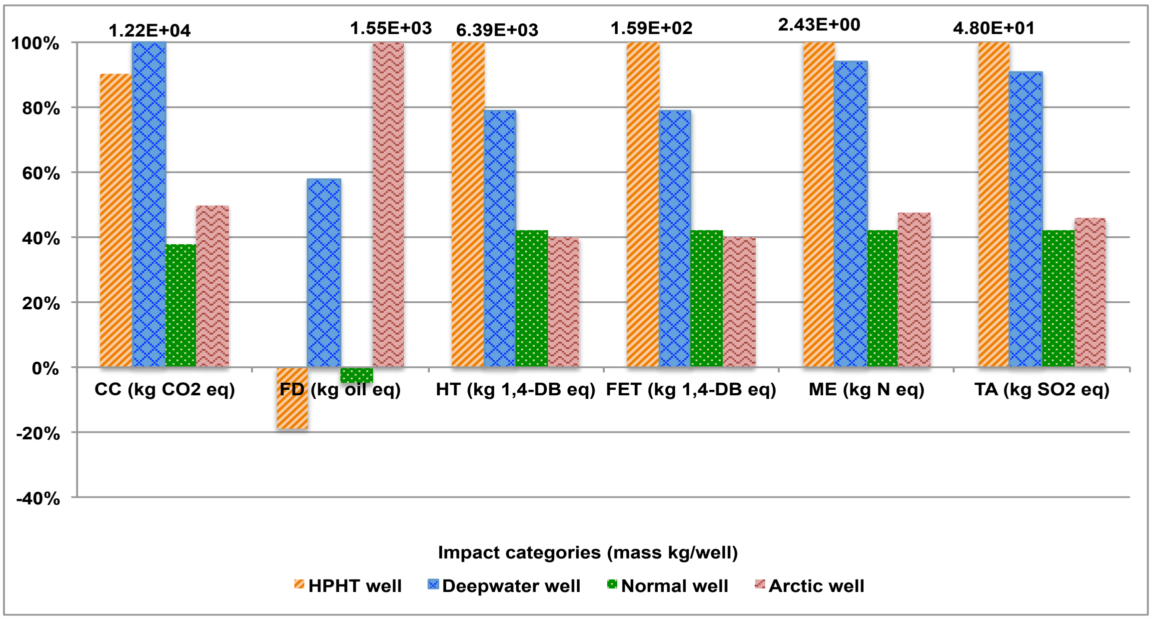


Figure 5.18. Comparison of onshore treatment systems impact assessment for all four well scenarios when oil is recycled

5.2.1 Comparison of normal and arctic well scenarios

The normal and arctic well scenarios were compared to highlight the impact contributions of oil and water based muds used for drilling. The lower section of the normal well as well as the HPHT and deep-water wells were drilled with an OBM, only the arctic well was drilled with drilled using only WBM.

First, results for the comparison of both offshore and onshore treatment systems applied for the treatment of arctic well slop is presented in figure 5.19. Onshore treatment emerged with the highest score overall, specifically in CC, FD categories where it is significantly dominated by slop transport to shore and in HT and FET categories where is dominated by both flocculation and biological treatment. The centrifuge system is highest in the ME and TA categories mainly due to the energy use of the disc stack centrifuge. The DAF system emerged with the lowest impact overall.

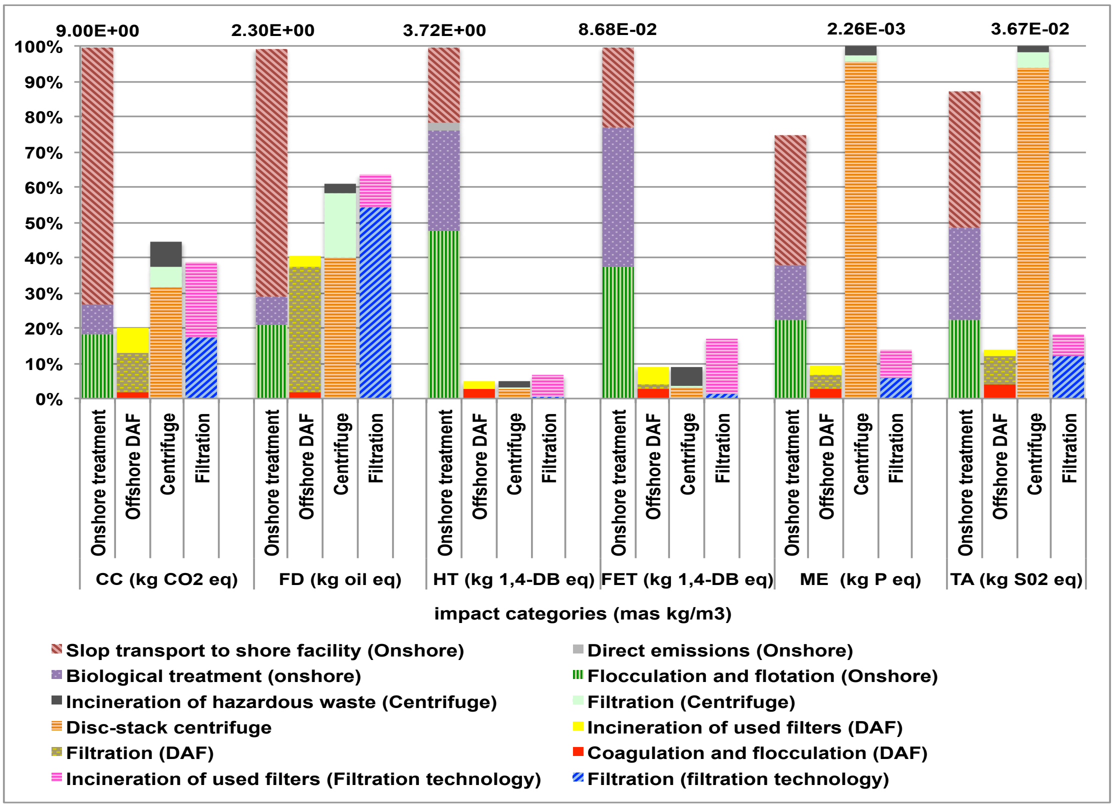


Figure 5.19. Comparative assessment of offshore and onshore treatment technologies for arctic well (excluding offshore injection)

The result presented in figure 5.20 is for the offshore technologies i.e. DAF, centrifuge and filtration, used for the treatment of lightly contaminated slop generated by both wells. It clearly shows that the higher scores of the DAF and centrifuge system of normal well relative to the arctic well is mainly due to the disposal of oily waste processes (for DAF this is represented by the "onshore treatment of sludge" process whose impact is mainly due to oily waste disposal and for centrifuge treatment the "incineration of filters and oily waste" is highly dominated by oily waste incineration).

This is particularly high in the CC, HT and FET categories where the scores are 46%, 62% and 78% for the DAF system of normal well relative to the incineration of only used filters for the DAF of arctic well whose scores are 1%, 6% and 12% respectively. Similarly for the centrifuge treatment of normal well slop, the same results are 57%, 57% and 87% compared to those of arctic well at 8%, 8% and 13% respectively. The total score of the filtration treatment is also slightly higher for the normal due to the relatively higher amount of filters consumed to remove oil from slop water. It would be expected that when oil is recycled, the results for normal and arctic wells will be more or less at par.

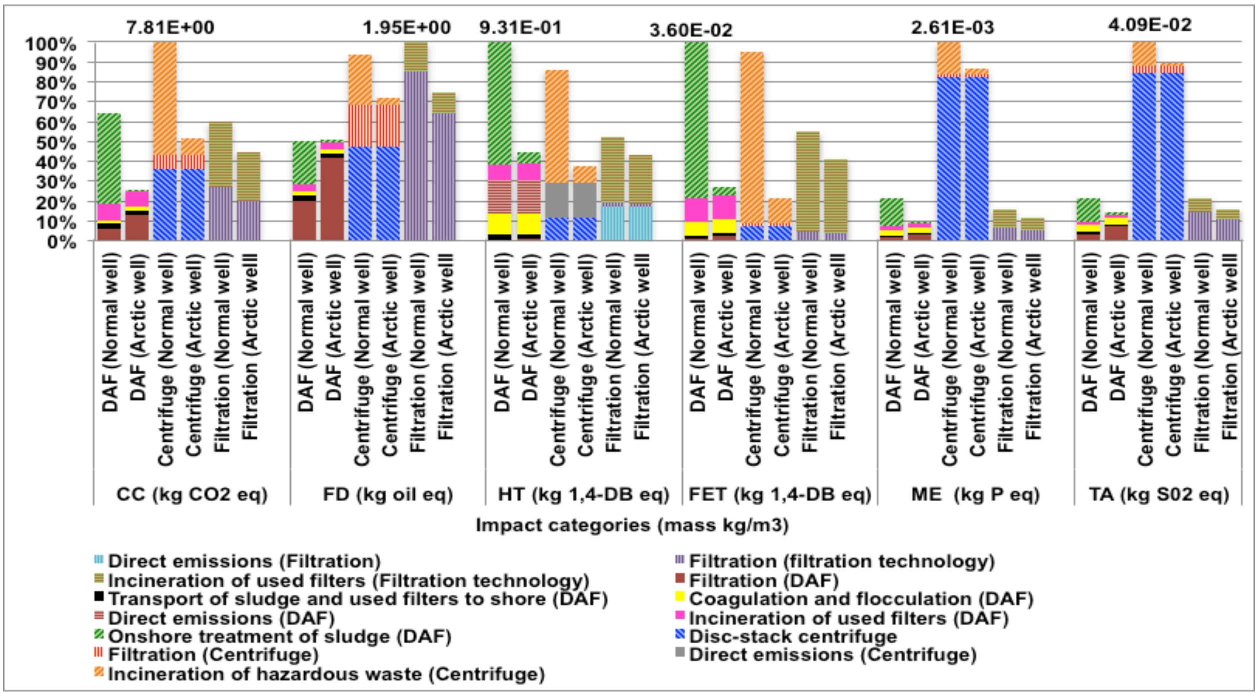


Figure 5.20. Comparative impact assessment of offshore treatment systems for normal and arctic wells (excluding offshore injection)

The results for the comparison of the onshore treatment systems is presented in figure 5.20 and shows that the "decanter" and "slop water transport to shore" are the processes that distinguishes both wells, as all the other processes have similar impact scores across the categories. The decanter process, whose impact is mainly due to oily waste disposal, contributed to making the normal well impact the highest in the CC and ME categories, however the slop water transport to shore which was relatively higher across all the categories contributed just enough to tip the arctic well scores above the normal well in the FD, FET and TA categories. The arctic and deep-water well the farthest to shore at 290km and 300km respectively. The HT category is about the same score for both well and largely dominated by the direct emissions process.

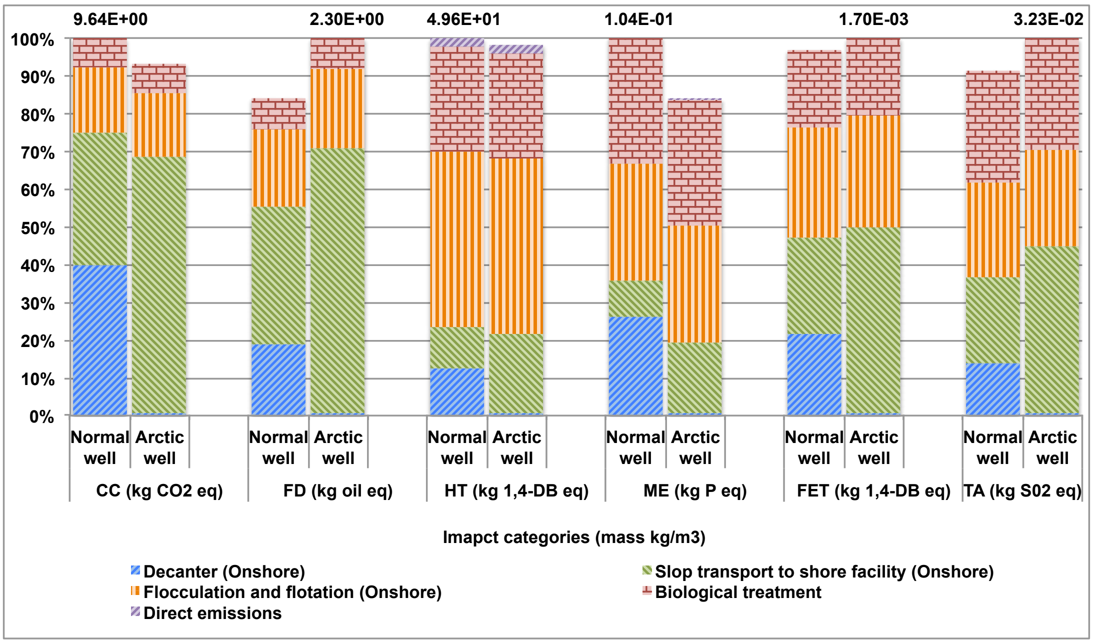


Figure 5.20. Comparative impact assessment of onshore treatment systems for normal and arctic wells

5.3 Sensitivity analysis

Due to the wide variations associated with drilling operations and considerable uncertainty inherent in the data and assumptions made, a sensitivity analysis was performed to understand the robustness of the results against changes in key parameters. Offshore energy was an important contributor to the impacts of offshore injection and centrifuge systems. Similarly transport of slop to shore was a significant contributor to the onshore treatment system impact. Hence the sensitivity of results to the choice of offshore energy and changes in transport efficiency were tested.

Offshore energy – natural gas turbines

Offshore (rig) energy is derived from diesel fuel burned in an electric generating set with an estimated efficiency of 28%. An alternative to this is the use of a natural gas turbine on platform, which is widely used offshore for power generation and runs on natural gas taken from the production process (HSE, 2006). Due to weight and space constraint on platforms, the offshore gas turbines are mostly simple-cycle types without heat recovery with a low energy conversion efficiency range of 25-35% relative to an ideal gas powered plant onshore with heat recovery which efficiency ranges between 60-80%.

Sensitivity test was performed by switching from diesel-based electricity to a natural gas based electricity process known as “natural gas on platform” and modelled by MISA. This resulted in an average reduction of 41% across all impact categories for the “slop injection energy process”.

The result is presented in appendix IV. A similar level of reduction was also observed for the centrifuge treatment system.

Offshore energy – electricity from onshore

The connection of offshore platforms to onshore electricity is increasingly becoming a subject of interest within the industry, but this may only be practical for development rigs rather than for exploratory drilling operations. Since the HPHT well scenario is a development drilling operation, the use of the relatively cleaner Norwegian electricity (Electricity, medium voltage {NO}|marked for| Alloc Def, U") was also tested which resulted in a reduction of 92% across the impacts for the slop injection energy process. The result is presented in appendix V. A similar level of reduction was also observed for the centrifuge system.

Improved efficiency of slop transport to shore

The process used for the transport of slop to shore in the onshore treatment system was modeled by MISA. It is modeled using a supply vessel that transports necessary commodities for crew and operation and returns slop to shore. It is estimated to have an efficiency of 50%. Depending on the service level, a test was performed for a 50% increase in efficiency for the transport of slop to shore process of the onshore treatment system for deepwater and arctic well scenario where they contribute significantly to impacts.

The results showed that for deep-water well, onshore treatment only became lower than the centrifuge system in the FD category and almost at par with the same system in the CD category while the DAF and filtration system remained unchanged with the lowest impacts for FD and CC respectively. For arctic well, a 50% improvement in efficiency only brought down onshore treatment system to par with offshore centrifuge and filtration systems in the FD category while it maintained its position in the other categories. However a 70% reduction brought it lower than centrifuge and filtration system in FD category and almost at par with both systems in CC category. However, the DAF system remained unchanged with the lowest impact overall. The results are provided in appendix VI.

6.0 Discussions

This section discusses the results based on decision objectives by first highlighting the best treatment system option for the normal well (baseline) scenario in terms of their impacts, after which variations in the impact results between the other well scenarios will be highlighted followed by a discussion of the implications for slop water management and summary of the uncertainties and quality of the inventories.

6.1 Well scenarios slop water volume and characteristics

The slop water generated by the normal well and the other 3 well scenarios differs mainly in terms of volume and oil content. The volume of lightly contaminated slop water for the normal, HPHT, deep-water and arctic is estimated to be 774 m^3, 1306 m^3 , 1846m m^3 and 660 m^3 respectively. The main sources of this type of slop water are rainwater or melted snow, rig wash water, tanks and pits cleaning water and displacement operations water interphase which are contaminated with oil due to the use of OBM.

Although the arctic well scenario did not involve the use of OBM, hence it's relatively smaller volume, the WBM used is assumed to contain hydrocarbon polymers that prohibited from discharge in the arctic environment.

The moderately contaminated slop is relatively smaller in volume mainly due to presence of higher oil content and does not significantly vary in volume and contamination level between the OBM drilled well scenarios i.e. 50 m^3 , 60 m^3 and 70 m^3 for normal, deep-water and HPHT respectively. The arctic well scenario does not produce this type of slop due to drilling with WBM only.

6.2 Normal well slop water treatment options performance

Based on the impact assessment results, the best overall treatment alternative for slop water generated by the normal well scenario is presented below and variations in the results between the well scenarios are highlighted afterwards.

Lightly contaminated slop water

When considering the treatment of lightly contaminated slop water offshore, the three offshore treatment systems which includes filtration, DAF and centrifuge treat technologies are far better alternatives compared to offshore injection disposal. Of the three offshore treatment systems assessed, the offshore filtration system emerges as the best alternative overall for the treatment of lightly contaminated slop when oil content of slop is not recycled.

When oil content of slop is recycled, of the three offshore treatment systems assessed, the best alternative treatment method shifts to the offshore DAF system overall. The sludge generated offshore is sent to shore for further processing to recover the oil and with a quality good enough for return to the crude oil side of refinery.

When considering the treatment of lightly contaminated slop water using either any of the offshore systems or sending it to shore for treatment, the offshore filtration treatment system still emerges as the best option when oil is not recycled, while DAF is the best option when oil is recycled. Aside the best-performing offshore treatment systems identified, the onshore treatment system performs better than the offshore injection system and also accrues additional benefits when the oil content is recycled, which leaves the offshore injection as the worst performing system overall.

Moderately contaminated slop water treatment

The volume of moderately contaminated slop water is generally considerably less than the lightly contaminated slop water stream especially when it is segregated at source. However, the volume can increase as a result of poor segregation due to a number of reasons which may include space constraints, poor rig practices etc. For the treatment of this slop water stream, the offshore DAF system emerges as the best alternative overall for both oil disposal and recycling scenarios. The filtration treatment is considered unsuitable for this type slop stream due to the higher oil content.

6.3 HPHT, deep-water and normal wells slop treatment performance variations

When considering the slop water generated by each well, the conclusion for HPHT and deep-water overall with regards to the dominating processes for each of the treatment systems across the impact categories is not significantly different from that of normal well for the treatment of both lightly and moderately contaminated slop water. The significant conclusion here is that the impact scores across all the categories and treatment systems increases in proportion to the volume and oil content of the slop water generated by each respective well. This explains why the impact scores of HPHT are higher than that of deep-water well overall. The same conclusion applies to the recycling scenario, meaning that the more the oil present in the slop water is recycled the greater the benefit.

One main challenge with the deep-water and HPHT wells is the limitation in rig storage capacity. Hence with the high volume of slop water generated, it becomes necessary to transport more of the slop water either to shore or for injection. If a decision is made to send slop water to shore for treatment, this becomes significant for the deep-water well scenario, which is the farthest from shore, twice the distance of normal well. The impact of such logistical demand is demonstrated by the result of the onshore treatment system in the deep-water well scenario where the transport of slop to shore did not only raise the FD score of the treatment system to almost equal that of HPHT level, but also cancelled out the benefits accrued from oil recycling.

6.4 Arctic well and normal well slop performance variations

For the arctic well scenario, the offshore DAF treatment emerges as the best alternative over the filtration treatment mainly due to less consumption of filter by DAF system as a result of a part removal of the oil and solids content of slop water by the coagulation and flocculation process prior to filtration stage. The uncertainties earlier described for the DAF system also applies to this scenario. The contrast between the results of the arctic and normal well clearly highlights both the significant effect of the drilling with OBM and logistics on slop water management. The contribution of the disposal/incineration of oily waste to the impact scores of the normal well across the categories of the treatment systems was clearly distinguished it from the arctic well scenario where only WBM was used. On the other hand, the onshore treatment system of the arctic well scenario well surpassed that of the normal well

6.5 Data quality and uncertainties

Primary data and information are hardly available and quite challenging to obtain from the industry for a number of reasons that includes process and chemical proprietary issues, wide variations in drilling operations and the presence of numerous players involved in any drilling operation at a time. Hence the data and relevant information used in this study are based on a variety of sources, which include published literatures, and conversation with operator and fluid/ oil services company employees.

The treatment technologies used in modelling of slop water treatment in this study have been selected based on their availability and popular application, yet this may not necessarily be representative of slop water treatment within the industry as there also a considerable number of other treatment technologies. Slop waste stream varies widely in composition, hence treatment has to be often tailored to meet discharge criteria. Though efforts were made to describe the sources, volumes and composition of slop water in this study in a way that suggests what obtains within the industry, the reality may vary quite significantly due to variability and complex nature of every single drilling operation.

The uncertainty level associated with the chemical inventories can be rated as medium. The chemicals used by the offshore treatment systems were based on commonly used or generic chemicals provided in published literatures and material safety data sheets. In reality, chemicals used to treat oily wastewater often involve a complex blend of chemicals, which are also evolving from time to time. The onshore treatment chemical inventory collected by Torp (2014) are mainly from Halliburton are relatively more reliable. The dose concentration reported are also based on published literature data, which are quite generic. Within the industry, chemical dose concentrations are normally determined by a laboratory jar test using the sample of the actual wastewater to be treated.

The offshore direct emissions data used were the same used in Torp (2014). These were not original data but were assumed to be similar to onshore emissions data, which were calculated as an average of yearly data reported by two slop water treatment facilities over a period of two years. As oil is the main component of slop water that needs to be removed prior to discharge, the treatment can be considered to be simple relative to onshore treatment, which suggests the level of direct emissions offshore is likely to be higher.

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7.0 CONCLUSION

The aim of this thesis was to contribute to the understanding of the environmental impacts of potential technological solutions for slop water management in different offshore drilling operations. To accomplish this, it was necessary to identify a range of slop water treatment technology options used offshore and onshore to treat different types and volumes slop water streams that were described and estimated based on wells drilled in different offshore drilling operation scenarios within the NCS. The treatment technology options were then evaluated using LCA and thereby providing a new level of detail that enhances/contributes towards the assessment of the attributes of stakeholders decision objectives on the environmental performance of offshore slop water management options their contributions to offshore drilling activities from a system perspective standpoint. Conclusions drawn from the evaluation are summarized below.

a. Utilisation of offshore treatment technology significantly minimises slop volume injected or sent to shore: Most offshore drilling operations waste plans are premised on the waste hierarchy which is considered as the guiding principle of waste management and ranks the waste management strategies in the prioritized order of source minimization, reuse, recycling, recovery, treatment and responsible disposal (OGP, 1993). This study demonstrates the use of environmentally friendly offshore treatment technological systems such as the filtration and DAF systems to treat slop water at source thereby reducing the volume of slop sent for injection or to shore and also potentially minimizes rig storage space required for the waste and logistics.

b. ***Offshore DAF treatment system offers the best solution in terms of environmental performance, flexibility and oil recycling:*** Whilst most rigs often have a water-oil separator or simple filtration system on board to handle lightly contaminated slop water, the DAF system offers a more flexible solution as it can handle both lightly and moderately contaminated slop water and also offers the potential to recycle the oil content of slop which makes it a more environmentally friendly option.

c. Oil contamination of slop water and handling matters: The environmental impact of oily waste incineration significantly dominated all the treatment systems for well scenarios that included the use of OBM. Hence it is worth taking efforts to minimize the contamination of slop with oil during drilling and also choosing a treatment method that is able to recover oil for reuse.

d. ***When slop water cannot be treated offshore at source, onshore treatment is a better alternative to offshore injection:*** Due offshore storage and treatment capacity limitation, there will be a need to send some of the slop water generated for injection or to shore for treatment.

This study shows that sending slop to shore for treatment is a better alternative relative to the offshore injection and it also offers the additional opportunity and benefits to recover and reuse the oil content of slop water, an option that is not available to offshore injection.

e. ***High slop volumes and logistics are main challenges for deep-water operations (including HPHT):*** Deep-water operations, which also include the HPHT drilling operations, are often located relatively father from shore and likely to generate high volumes of slop water due to long drilling duration and well depth. This implies a logistical challenge, as more slop will have to be shipped to shore over a long distance with significant environmental impacts.

f. ***Key challenges for the arctic well scenario includes stricter environmental regulations, logistics and proximity of treatment facilities***: Whilst OBM is currently not allowed for drilling in the arctic, considerations will still have to be given to the components of drilling fluids as a wide range of chemicals are prohibited from discharge which can also influence slop volumes. A zero-discharge regime is in place in the arctic, which in other words, means that offshore discharge regulations are generally stricter and injection to subsea option is scarcely available. Hence, logistics becomes a main challenge due to harsh environmental conditions, long distance to shore and the fewer availability local facilities.

g. Alternative rig energy sources such as natural gas and onshore electricity offers considerable reduction in impacts: The use of alternative source of rig energy such as natural gas or onshore electricity (only practical for development wells) can significantly reduce the impacts arising from energy use by offshore slop water treatment system such as the centrifuge system, which is more energy dependent, as well a reduction in impacts of offshore injection. Though it is still likely to have a worst performance than the onshore treatment options.

7.1 Effect of offshore slop water volume minimisation

There a number of identified opportunities to minimize slop volume offshore which includes good housekeeping to minimize spills on deck, use of vacuum units to remove oil spills, use of high-pressure low-volume water hoses to reduce deck-cleaning, recycling of tank cleaning water, improved well-bore clean up practices, all of which can potentially reduce the volume of slop water by an estimated 40-45% (Okiemute, 2013). This is particularly relevant for the deep-water and HPHT wells where high volumes are generated and can have a considerable effect on slop management approaches in terms of proportional reduction in impacts, volume of slop injected, tonnages and emissions due to logistics, chemical and energy consumption during treatment.

7.2 Recommendations for future work

Areas relevant to a better understanding and evaluation of slop wastewater management not covered in this study but can be the focus of future study is:

- A better description and modelling of oil recovery from slop water. This could cover the intact recovery of drilling fluid from moderately contaminated which can be readily reused in the active system or reused as a raw material for drilling fluids manufacturing or other uses.
- A better understanding of the potential benefits of treated water reuse where possible.
- A better description and modelling of slop logistics both offshore and onshore.
- Impacts associated with the construction phase of offshore treatment modular units.
- Improvement in the uncertainty associated chemicals and energy inputs of treatment technologies through the development of modified and relevant inventory inputs.
- Further work on the effect of discharges made off shore, as well as from the final treatment of sludge wastes.

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Appendix I. Offshore injection disposal inventory

Functional unit is the drilling of a well but values given here is per m^3 of treated slop water.

Construction of an injection well				
Processes	**Materials and Energy (as used in Simapro)**	**Amount**	**Unit**	**Source and Comment**
Drilling operations	Drilling operations, on production site (only derrick and rotary)	25	day	Foreground data based on Saasen et al., (2014). Process modelled by MISA.
Drilling mud	Glydril WBM (1.25 sg)	450	m3	Foreground data based on Saasen et al., (2014). Process modelled by MISA.
Well bore casings	Construction 36" section casing (30")	30	m	Foreground data based on generic estimate by Torp (2014). Process modelled by MISA.
	Construction 16" section casing (13 3/8")	570	m	Foreground data based on Saasen et al., (2014). Process modelled by MISA.
	Construction 13 5/8" section casing (13 5/8")	412	m	
Supply/transport	Far Serenade, at economy speed (11.3 kn)	328.8	hr	Foreground data based on Saasen et al., (2014). Process modelled by MISA.
	Transport, helicopter {GLO}|market for| Alloc Def, U	33	hr	Foreground data based on Saasen et al., (2014). Process modelled by MISA.
Fracking liquid	Carboxymethyl cellulode, powder {GLO}|market for| Alloc Def, U	4200	kg	Ecoivent process substitution for hydroxyethyl cellulose, amount from (AEA, 2012).
Slop injection into well				
Processes	**Materials and Energy (as used in Simapro)**	**Amount**	**Unit**	**Source and Comment**
Energy for pumping slop	Electricity, diesel-electric on drilling rig offshore, 28% efficicency	142	kWh	Foreground data based on NOGA and James et al. (2002). Process modelled by MISA.
Plug and abandonment of well				
Processes	**Materials and Energy (as used in Simapro)**	**Amount**	**Unit**	**Source and Comment**
Rig operations	Drilling operations, on production site (only derrick and rotary)	10	days	Foreground data based on Saasen et al., (2014). Process modelled by MISA.
Supply/transport	Transport, helicopter {GLO}|market for| Alloc Def, U	14	hr	Process modelled by MISA and foreground data based on Saasen et al., (2014)
	Far Serenade, at economy speed (11.3 kn)	81.6	hr	Process modelled by MISA and foreground data based on Saasen et al., (2014)
Cement plug	Cement,Portland {CH}|production|Alloc Def,U	7680.6	kg	Material is from Ecoivent and cement plug length based on Cement plug OISD (2013).

Appendix II. Onshore treatment system inventory

Flocculation and floatation	**Chemicals (as used in Simapro)**	**Amount (kg/m3)**	**Source and comment**
	Sodium Hydroxide 30%	9.90E-02	Foreground data developed and estimated by Torp (2014) based on material data sheet provided by Halliburton. Ecoinvent material.
	UNIFLOC AE 300	3.20E-02	
	Hydrochloric acid, without water, in 30% solution state {RER}|hydrochloric acid production from the reaction of hydrogen with clorine| All Def, U	3.00E-01	Foreground data provided by Halliburton according to Torp (2014). Ecoinvent material
	Iron (III) chlorine, 40% in H2O, at plant/CH U	1.00E+00	
	Benzal chloride {GLO}|market for| Alloc Def, U	4.90E-02	Ecoinvent material substitution for BAC 50. Foreground data provided by Halliburton according to Torp (2014
	Tap water, at user/RER U	6.57E+02	Foreground data estimated by Torp (2014) based on information provided by Halliburton. Ecoinvent material.
	Energy (as used in Simapro)	**Amount (kWh/m3)**	**Source and comment**
	Electricity, low voltage, production NO, at grid/NO U	3.30E-01	Foreground data provided by Halliburton according to Torp (2014). Ecoinvent energy
Biological treatment	**Chemicals (as used in Simapro)**	**Amount (kg/m3)**	**Source and comment**
	Flex Bio 10-7	1.91E+00	Foreground data developed and estimated by Torp (2014) based on material data sheet provided by Halliburton. Ecoinvent material.
	STRUKTOL SB 2080	2.00E-02	
3-phase decanter	**Energy (as used in Simapro)**	**Amount (kWh/m3)**	**Source and comment**
	Electricity, low voltage, production NO, at grid/NO U	2.12E+00	Foreground data based on Roger Kahlil 2007, stating 1-2 kWh/m3 for decanters. Ecoinvent energy.
	Chemicals/materials (as used in Simapro)	**Amount (kg/m3)**	**Source and comment**
	Polyacrylamide, at production	2.12E+00	MISA inventory substitute for Nalco, ULTIMER 7752. Foreground data provided by Halliburton (Torp, 2014).
	Tap water, at user/RER U	1.95E+02	Estimated based on data provided by Halliburton (Torp, 201). Ecoinvent energy.
Outputs	**Materials (as used in Simapro)**	**Amount (kg/m3)**	**Source and comment**
	Crude oil, at production offshore/NO U	1.57E+00	Ecoinvent material substitute for recovered oil. Foreground data estimated by mass balance data from Flottweg (2015), Hiller-US (2015)
Direct emissions	**Chemicals (as used in Simapro)**	**Amount (kg/m3)**	**Source and comment**
	Arsenic	1.81E-05	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
	Barium	2.22E-03	
	Chromium	3.36E-05	
	Cadmium	9.27E-07	
	Copper	4.44E-05	
	Molybdenum	1.77E-04	
	Nickel	3.38E-04	
	Oils, biogenic	4.52E-03	
	Lead	7.15E-06	
	Tin	1.52E-05	
	TOC, Total Organic Carbon	8.00E-01	
	Vanadium	1.33E-05	
	Zinc	9.35E-05	

Transport of slop to shore	**Inputs - materials/fuels (as used in Simapro)**	**Amount (tkm)**	**Source and comment**
Normal well	Supply boat, transport (includes standby time)	1.17E+05	Based on a distance of 150km from field to shore. Process modelled by MISA.
Deepwater well		3.96E+05	Based on a distance of 300km from field to shore. Process modelled by MISA.
HPHT well		2.80E+05	Based on a distance of 240km from field to shore. Process modelled by MISA.
Arctic well		1.93E+05	Based on a distance of 290km from field to shore. Process modelled by MISA.
Infrastructure	**Inputs - materials/fuels (as used in Simapro)**	**Amount (p)**	**Source and comment**
	Wastewater treatment facility, capacity 1,6E8l/year {CH}l construction l Alloc Def, U	0.000158	Waste water treatment class 5, based on the description in Ecoinvent manual.
Disposal	**Outputs (as used in Simapro)**	**Amount (p)**	**Source and comment**
	Disposal, hazardous waste, 25% water, to hazardous waste incineration/CH U	1.57E+00	Ecoivent material substitute for oily waste from decanter. Foreground data estimated by mass balance.
	Disposal, inert waste, 5% water, to inert material landfill	3.49E+00	Ecoivent material substitute for solid waste from decanter. Foreground data estimated by mass balance.

Appendix II1. Offshore treatment systems inventory

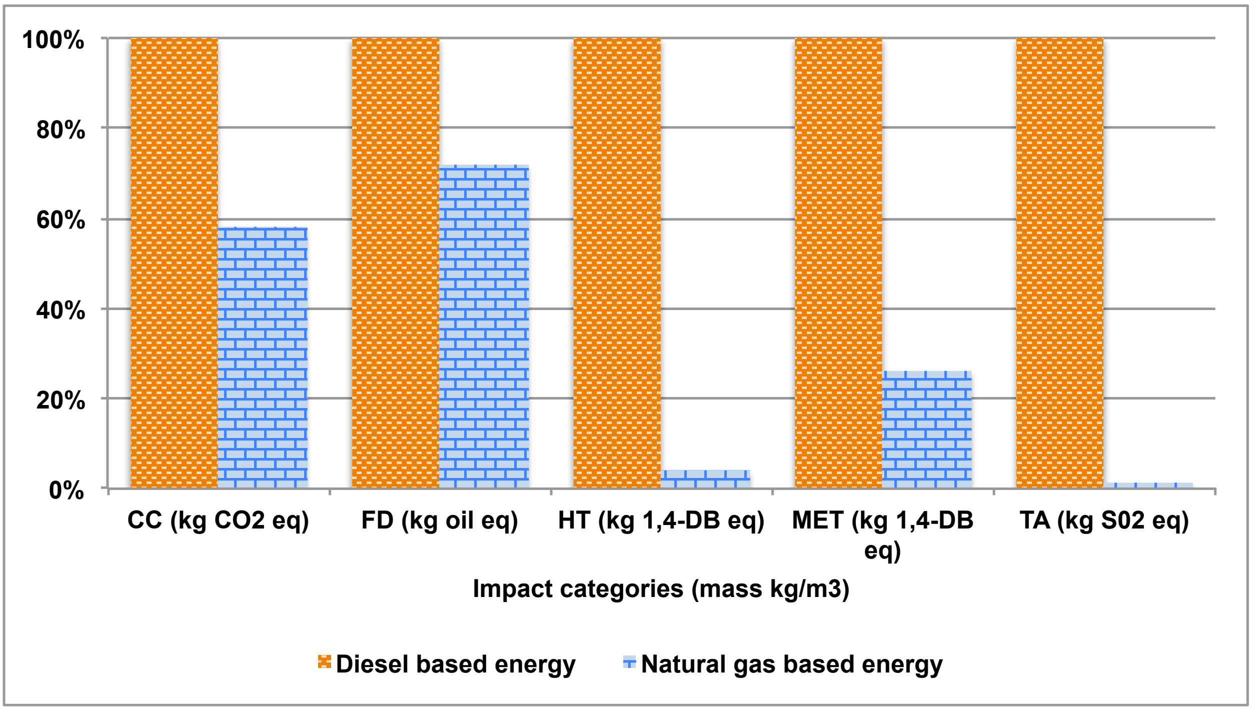
Filtration treatment system			
Slop water feed energy	**Inputs - materials/fuels (as used in Simapro)**	**Amount (kg/m3)**	**Source and comment**
	Electricity, diesel-electric on drilling rig offshore, 28% efficicency	8.00E-02	Based on a mono feed pump with a capacity of 0.75kW used for 6hrs/day with a flow rate of $60m^3$/day. Energy process modelled by MISA.
Filtration	**Inputs - materials/fuels (as used in Simapro)**	**Amount (kg/m3)**	**Source and comment**
	Polypropylene, granulate, at plant/RER/ U.	1.06E+00	Estimates based on 0.53kg of media/m3 and 90% polypropylene composition (Twinfilter.com, 2015). Amount doubled to account for extra demand to remove oil and solids. Ecoinvent material.
Transport of used filters to shore	**Inputs - materials/fuels (as used in Simapro)**	**Amount (tkm/m3)**	**Source and comment**
Normal well	Supply boat, transport (includes standby time	1.59E-01	Based on a used filters weight and distance of 150km from field to shore.
Deepwater well		3.17E-01	Based on a used filters weight and distance of 300km from field to shore.
HPHT well		2.54E-01	Based on a used filters weight and distance of 240km from field to shore.
Arctic well		1.21E-01	Based on a used filters weight and distance of 290km from field to shore.
Transport of waste to disposal site	**Inputs - materials/fuels (as used in Simapro)**	**Amount (tkm/m3)**	**Source and comment**
Normal well	Cargoship, average NO, travelling	5.30E-01	Based on estimated distance of 500km from treatment facility in Mongstad to incineration site.
Deepwater well		1.58E+00	Based on estimated distance of 1500km from treatment facility in Sandnesjoen to incineration site.
HPHT well		1.06E+02	Based on estimated distance of 1000km from treatment facility in Kristiansund to incineration site.
Arctic well		1.59E+02	Based on estimated distance of 200km from treatment facility in Hammerfest to incineration site.
Direct emissions	**Inputs - materials/fuels (as used in Simapro)**	**Amount (tkm/m3)**	**Source and comment**
	Arsenic	1.81E-05	All offshore direct emissions is assumed to be similar to that of onshore treatment system but with the inclusion of Benzene ethyl.
	Barium	2.22E-03	
	Benzene, ethyl	1.12E-05	
	Chromium	3.36E-05	
	Cadmium	9.27E-07	
	Copper	4.44E-05	
	Molybdenum	1.77E-04	
	Nickel	3.38E-04	
	Oils, biogenic	4.52E-03	
	Lead	7.15E-06	
	Tin	1.52E-05	
	TOC, Total Organic Carbon	8.00E-01	
	Vanadium	1.33E-05	
	Zinc	9.35E-05	

DAF treatment system			
Slop water feed energy	**Inputs - materials/fuels (as used in Simapro)**	**Amount (kg/m3.)**	**Source and comment**
	Electricity, diesel-electric on drilling rig offshore, 28% efficicency	8.00E-02	Based on a mono feed pump with a capacity of 0.75kW used for 6hrs/day with a flow rate of 60m^3/day. Energy process modelled by MISA.
Coagulation and flocculation	**Inputs - materials/fuels (as used in Simapro)**	**Amount (kg/m3)**	**Source and comment**
	Aluminium sulphate, powder, at plant/RER U.	1.20E-01	Estimated based on dosing cencentration reported in Puszkarewicz (2008), Eckenfelder (1989), Mohammed et al (2005); and Sharaai et al.,(2010).Ecoinvent material.
	Bentonite at processing/DE U.	5.00E-03	Estimate based on Armenante (no date) and Puszkarewicz (2008) .Ecoinvent material.
	Sodium hydroxide, 50% in H2O, production mix, at plant/RER U.	3.00E-02	Estimate based on TAUD, 2004. Mohammed et al. 2005 ; Thamer (2005) .Ecoinvent material.
Dissolved air flotation (DAF)	**Inputs - materials/fuels (as used in Simapro)**	**Amount (kg/m3)**	**Source and comment**
	Electricity, diesel-electric on drilling rig offshore, 28% efficicency	2.07E-01	Estimated based on two 0.19KW pump used for 2hrs/day for dosing. Stirring was not considered. Energy process modelled by MISA
Filtration	**Inputs - materials/fuels (as used in Simapro)**	**Amount (kg/m3)**	**Source and comment**
	Polypropylene, granulate, at plant/RER/ U.	2.65E-01	Estimates based on 0.53kg/m3 and 90% polypropylene composition (Twinfilter.com, 2015). Amount reduced by 50% due to prior removal of oil and solids druing coagulation and flocculation.. Ecoinvent material.
Transport of sludge and used filters to shore	**Inputs - materials/fuels (as used in Simapro)**	**Amount (tkm/m3)**	**Source and comment**
Normal well	Supply boat, transport (includes standby tin	7.98E+00	Based on a used filters weight and distance of 150km from field to shore.
Deepwater well		1.62E+01	Based on a used filters weight and distance of 300km from field to shore.
HPHT well		1.22E+01	Based on a used filters weight and distance of 240km from field to shore.
Arctic well		6.89E+00	Based on a used filters weight and distance of 290km from field to shore.
Onshore treatment of DAF sludge			
Flocculation and floatation	**Inputs - materials/fuels (as used in Simapro)**	**Amount (kg/m3)**	**Source and comment**
	Sodium Hydroxide 30%	9.90E-02	Foreground data developed and estimated by Torp (2014) based on material data sheet provided by Halliburton. Ecoinvent material.
	UNIFLOC AE 300	3.20E-02	
	Hydrochloric acid, without water, in 30% solution state {RER}lhydrochloric acid production from the reaction of hydrogen with clorinel All Def, U	3.00E-01	Foreground data provided by Halliburton according to Torp (2014). Ecoinvent material
	Iron (III) chlorine, 40% in H2O, at plant/CH U	1.00E+00	
	Benzal chloride {GLO}lmarket forl Alloc Def, U	4.90E-02	Ecoinvent material substitution for BAC 50. Foreground data provided by Halliburton according to Torp (2014
	Tap water, at user/RER U	6.57E+02	Foreground data estimated by Torp (2014) based on information provided by Halliburton. Ecoinvent material.
	Energy (as used in Simapro)	**Amount (kWh/m3)**	**Source and comment**
	Electricity, low voltage, production NO, at grid/NO U	3.30E-01	Foreground data provided by Halliburton according to Torp (2014). Ecoinvent energy

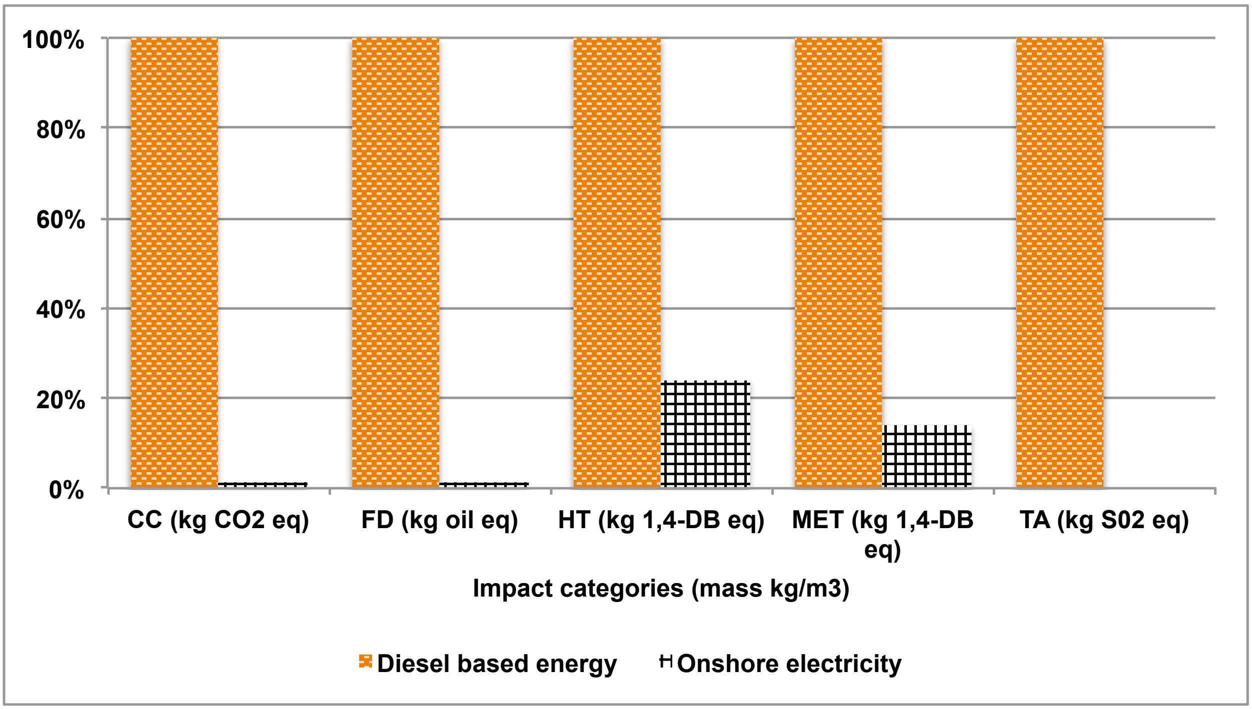
Biological treatment	**Inputs - materials/fuels (as used in Simapro)**	**Amount (kg/m3)**	**Source and comment**
	Flex Bio 10-7	1.91E+00	Foreground data developed and estimated by Torp (2014) based on material data sheet provided by Halliburton. Ecoinvent material.
	STRUKTOL SB 2080	2.00E-02	
3-phase decanter	**Energy (as used in Simapro)**	**Amount (kWh/m3)**	**Source and comment**
	Electricity, low voltage, production NO, at grid/NO U	2.12E+00	Foreground data based on Roger Kahlil 2007, stating 1-2 kWh/m3 for decanters. Ecoinvent energy.
	Chemicals/materials (as used in Simapro)	**Amount (kg/m3)**	**Source and comment**
	Polyacrylamide, at production	2.12E+00	MISA inventory substitute for Nalco, ULTIMER 7752. Foreground data provided by Halliburton (Torp, 2014).
	Tap water, at user/RER U	1.95E+02	Estimated based on data provided by Halliburton (Torp, 201). Ecoinvent energy.
Outputs	**Materials (as used in Simapro)**	**Amount (kg/m3)**	**Source and comment**
	Crude oil, at production offshore/NO U	1.41E+00	Assume oil is recovered. Ecoinvent material substitute for recovered oil. Foreground data estimated by mass balance data from Flottweg (2015), Hiller-US (2015)
Transport of waste to disposal site	**Inputs - materials/fuels (as used in Simapro)**	**Amount (tkm/m3)**	**Source and comment**
Normal well	Cargoship, average NO, travelling	9.11E-01	Assumed no oil recovery; transport of oily waste and used filters. Transport of used filter only neglible. Based on distance of 500km from facility in Mongstad to site.
Deepwater well		2.55E+00	Same assumption as normal well. Distance of 1500km from Sandnesjoen to incineration site.
HPHT well		1.71E+00	Same assumption as normal well. Distance of 1000km from Kristiansund to incineration site.
Arctic well		5.06E-01	Same assumption as normal well. Distance of 2000km from Hammerfest to incineration site.
Infrastructure	**Inputs - materials/fuels (as used in Simapro)**	**Amount (p/m3)**	**Source and comment**
	Wastewater treatment facility, capacity 1,6E8l/year {CH}| construction | Alloc Def, U	1.58E-04	Waste water treatment class 5, based on the description in Ecoinvent manual.
Disposal	**Outputs (as used in Simapro)**	**Amount (kg/m3)**	**Source and comment**
	Disposal, hazardous waste, 25% water, to hazardous waste incineration/CH U	1.66E+00	Ecoivent material substitute for oily waste from decanter and used filters from offshore.Assume oil is disposed. Disposal of used filter alone is negligible Foreground data estimated by mass balance.
	Disposal, inert waste, 5% water, to inert material landfill	3.10E+00	Ecoivent material substitute for solid waste from decanter. Foreground data estimated by mass balance.

Centrifuge treatment system			
Decanter feed energy	**Inputs - materials/fuels (as used in Simapro)**	**Amount (kg/m3.)**	**Source and comment**
	Electricity, diesel-electric on drilling rig offshore, 28% efficicency	8.00E-02	Based on a mono feed pump with a capacity of 0.75kW used for 6hrs/day with a flow rate of 60m^3/day. Energy process modelled by MISA.
3-phase decanter	**Energy (as used in Simapro)**	**Amount (kWh/m3)**	**Source and comment**
	Electricity, diesel-electric on drilling rig offshore, 28% efficiency	2.50E+00	Foreground data based on Roger Kahlil 2007, stating 1-2 kWh/m3 for decanters. Energy process modelled by MISA.
	Chemicals/materials (as used in Simapro)	**Amount (kg/m3)**	**Source and comment**
	Polyacrylamide, at production	2.12E+00	MISA inventory substitute for Nalco, ULTIMER 7752. Foreground data provided by Halliburton (Torp, 2014).
	Tap water, at user/RER U	1.95E+02	Estimated based on data provided by Halliburton (Torp, 201). Ecoinvent energy.
Outputs	**Materials (as used in Simapro)**	**Amount (kg/m3)**	**Source and comment**
	Crude oil, at production offshore/NO U	1.57E+00	Assume oil is recovered. Ecoinvent material substitute for recovered oil. Foreground data estimated by mass balance data from Flottweg (2015), Hiller-US (2015)
Filtration	**Inputs - materials/fuels (as used in Simapro)**	**Amount (kg/m3)**	**Source and comment**
	Polypropylene, granulate, at plant/RER/ U.	2.65E-01	Estimates based on 0.53kg/m3 and 90% polypropylene composition (Twinfilter.com, 2015). Amount reduced by 50% due to prior removal of oil and solids by decanter. Ecoinvent material.
Transport of oil and waste to shore	**Inputs - materials/fuels (as used in Simapro)**	**Amount (tkm/m3)**	**Source and comment**
Normal well	Supply boat, transport (includes standby time)	4.16E-03	Based on transport used filters, solids and recovered oil/oily waste when oil is not recoverd weight. Distance of 150km from field to shore.
Deepwater well		4.24E-03	Same assumption as normal well. Distance of 300km from field to shore.
HPHT well		4.28E-03	Same assumption as normal well. Distance of 240km from field to shore.
Arctic well		2.27E-03	Transport of used filter and solids from decanter only. No oily waste. Distance of 290km from field to shore.
Transport of waste to disposal site	**Inputs - materials/fuels (as used in Simapro)**	**Amount (tkm/m3)**	**Source and comment**
Normal well	Cargoship, average NO, travelling	9.17E-01	Assumed no oil recovery; transport of oily waste and used filters. Transport of used filter only neglible. Distance of 500km from facility in Mongstad to site.
Deepwater well		2.81E+00	Same assumption as normal well. Distance of 1500km from Sandnesjoen to incineration site.
HPHT well		1.87E+00	Same assumption as normal well. Distance of 1000km from Kristiansund to incineration site.
Arctic well		5.30E-01	Same assumption as normal well. Distance of 2000km from Hammerfest to incineration site.
Disposal	**Outputs (as used in Simapro)**	**Amount (kg/m3)**	**Source and comment**
	Disposal, hazardous waste, 25% water, to hazardous waste incineration/CH U	1.83E+00	Ecoivent material substitute for oily waste from decanter and used filters from offshore.Assume oil is disposed. Disposal of used filter alone is negligible Foreground data estimated by mass balance.
	Disposal, inert waste, 5% water, to inert material landfill	3.49E+00	Ecoivent material substitute for solid waste from decanter. Foreground data estimated by mass balance.

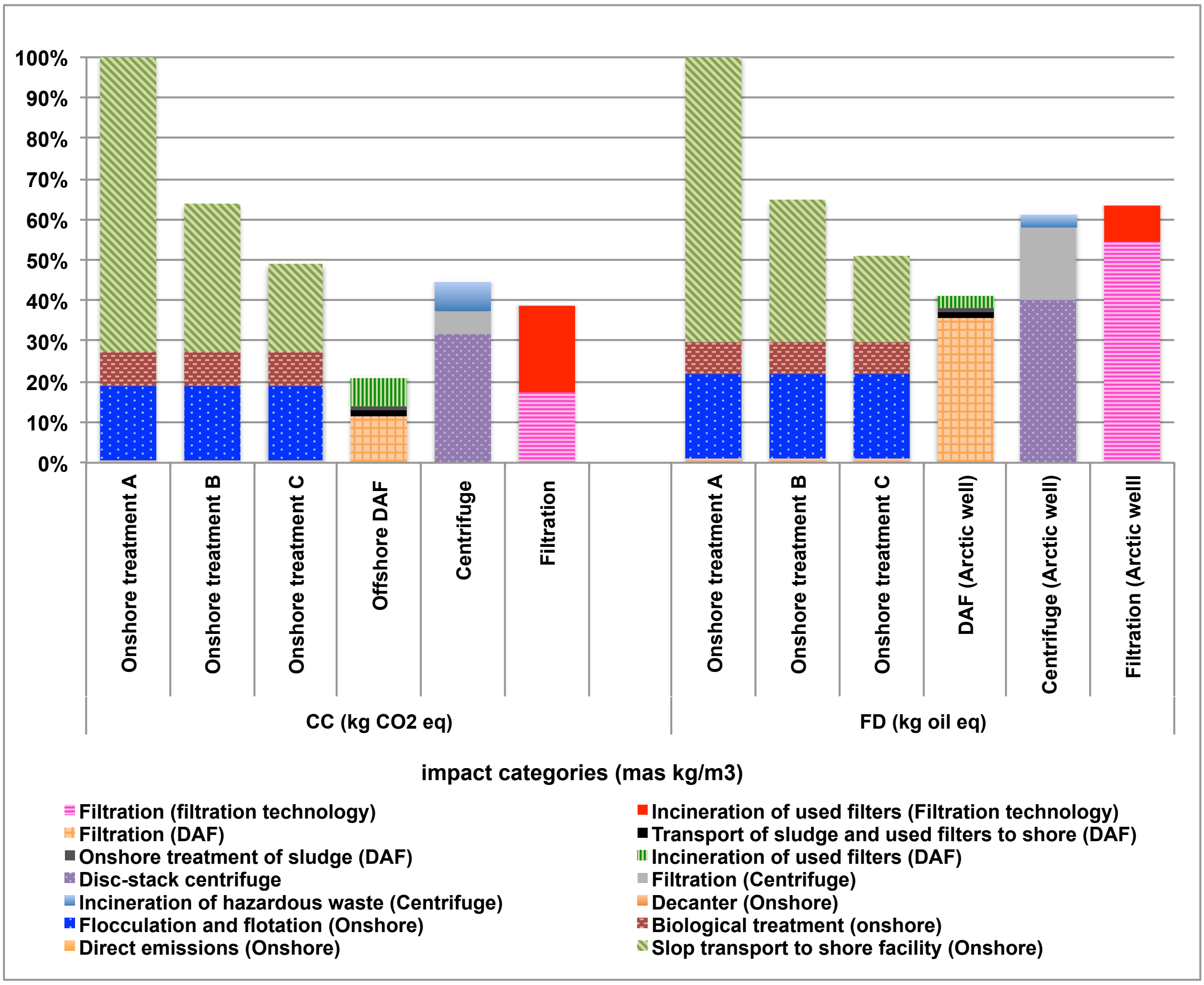
Appendix IV: Sensitivity analysis result for alternative offshore energy (natural gas)



Appendix V: Sensitivity analysis result for alternative offshore energy (onshore electricity)



Appendix VI. Sensitivity analysis result for efficiency of transport of slop to shore



Onshore treatment A = MISA transport model estimated at 50% efficiency

Onshore treatment = 50% efficiency improvement in MISA's model

Onshore treatment = 70% efficiency improvement in current in MISA's model