CHALMERS
UNIVERSITY OF TECHNOLOGY

Applying circular economy principles in the oil & gas industry

An LCA study of the decommissioning process of offshore platforms

Master's thesis in the Industrial Ecology Program

AIKATERINI TERPOU

Department of Energy and Environment
Division of Environmental Systems Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2017
Report no. 2017:3

REPORT. 2017:3

Applying circular economy principles in the oil & gas industry

An LCA study of the decommissioning process of offshore platforms

Master's Thesis within the *Industrial Ecology* program

AIKATERINI TERPOU

Department of Energy and Environment

Division of Environmental Systems Analysis

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2017

Applying circular economy principles in the oil & gas industry
An LCA study of the decommissioning process of offshore platforms

Master's thesis within the *Industrial Ecology* program

AIKATERINI TERPOU

Supervisor: Matty Janssen
Examiner: Sverker Molander

Report no. 2017:3

Department of Energy and Environment

Division of Environmental Systems Analysis

Chalmers University of Technology

SE-41296 Gothenburg, Sweden

Telephone: +30 6940530860

Chalmers Reproservice
Gothenburg, Sweden 2017

Applying circular economy principles in the oil & gas industry
An LCA study of the decommissioning process of offshore platforms
Master’s thesis within the *Industrial Ecology* program
AIKATERINI TERPOU
Department of Energy and Environment
Division of Environmental Systems Analysis
Chalmers University of Technology

Abstract

Many offshore platforms are soon to reach or have already reached their mature phase, which means that in the foreseeable future, measures will need to be taken for their eventual removal. After their decommissioning, these platforms are a potential source of huge amounts of materials. The current study aimed to investigate how the oil & gas industry can improve its environmental performance by implementing the Circular Economy principles during the decommissioning process. More concretely, it was hypothesized that the environmental performance of the system would change if reuse was involved in the final stages of decommissioning. For these purposes, the Life Cycle Assessment procedure was implemented.

The results show that partial decommissioning is a better option than complete decommissioning due to lower energy use during recycling and transportation. The results of a reuse scenario suggest that the environmental impacts of both decommissioning methods are reduced. Sensitivity analysis indicated that when the percentage of reuse is increased, the performances of complete and partial decommissioning from an environmental perspective both improve.

This thesis concludes that optimising marine vessels used for transporting a platform’s pieces could help reduce emissions from that particular process. At the same time, reducing the amount of material that goes to recycling by increasing the reuse of certain assets of the platform, would improve the environmental performance of these decommissioning stages. It was also identified that there is a need for data transparency in the decommissioning field in order to produce more certain and accurate results.

Keywords: offshore platform, decommissioning, Life Cycle Assessment, Reuse, Circular Economy

Acknowledgements

I would first like to thank my thesis supervisor Matty Janssen for his valuable feedback and help. He was always available whenever I ran into difficulties and whenever I had questions regarding my research. I would also like to express my gratitude to Sverker Molander for taking the role as my examiner.

I would also like to thank my parents, who have always stood by me with unconditional love and patience. To my siblings, Chris and Anastasia, thank you for supporting me through my ups and downs. My sincere thanks to Julia, for motivating me up until the very end me to continue this work. Thank you to my friends, those near home and the ones far away, for listening to me and cheering me up through the process of researching and writing this thesis. Special thanks to Gulnara; you were ready to listen and calm me down more times than I can count.

Finally, I would like to thank Chalmers University of Technology for giving me a chance to study in a different country, where I met the most extraordinary people and experienced unforgettable moments.

Abbreviations

UKCS	United Kingdom Continental Shelf
NCS	Norwegian Continental Shelf
CE	Circular Economy
EoL	End –of-Life
VOC	Volatile Organic Compound
OSPAR	Convention for the Protection of the Marine Environment of the Northeast Atlantic
UNCLOS	The United Nations Convention on the Law of the Sea
IMO	International Maritime Organisation
CoP	Cessation of Production
HLV	Heavy Lift Vessels
GWP	Global Warming Potential
EP	Eutrophication Potential
AP	Acidification Potential

Figure list

Table list

Table of Contents

1. Introduction

In the early 2000s, there were more than 6500 offshore oil and gas installations around the world, located on the continental shelves of several countries. The Gulf of Mexico, the Middle East, Asia, North East Atlantic and North Sea were the main areas, where most of the platforms were situated (Osmudsen & Tveteras, 2003). Currently, the North Sea contains around 400 fixed platforms, installed on either the United Kingdom Continental Shelf (UKCS), the Norwegian Continental Shelf (NCS), or are property of Denmark and the Netherlands (Swartz, 2015). Many platforms are soon to reach or have already reached their mature phase, which means that in the foreseeable future, measures will need to be taken for their eventual removal. The process of removing an oil & gas platform is formally known as decommissioning and the actions taken to complete it come with significant environmental, economic and social consequences. After their decommissioning, these platforms are a potential source of huge amounts of materials. In the UKCS alone, the emplaced steel structures are composed of about 2.3 million tons of steel (Scottish Enterprise, 2002).

At the same time, the concept of Circular Economy (hereinafter referred to as CE) and its principles have sparked the interest of the oil and gas industry due to the possibilities of enhancing economic value and reducing the waste generated during decommissioning. In a general context, CE mimics the natural life cycles where dead organisms become food for the future living organisms. As in nature, circular economy follows a “cradle-to-cradle” principle where waste becomes resource (Andrews, 2015). It implies a model where the use of raw materials is minimized during a production process, where waste can be reused as a resource in various ways, and where a product can be used several times for the purpose it was originally made instead of having a one-time use (Zhijun & Nailing, 2007). According to the *Growth Within: a circular economy vision for a competitive Europe* report by the Ellen MacArthur Foundation (2015), the concept of circular economy is built upon three fundamental principles: (i) preserve and enhance natural capital, (ii) optimize yields from resources in use and, (iii) foster system effectiveness.

Most commonly, materials collected from an offshore platform are sent to recycling facilities. Green Alliance, a UK organisation, produced a report (Benton, 2015) in partnership with the Scottish Council for Development and Industry, in which they described the ways the oil & gas industry can adapt a more CE approach. In the report, they suggested various options, ranking from least to most radical. The least radical option was to improve the separation of high quality metal alloys, which would result in more effective recycling. The next best option was considered to be the reuse of platform assets, a trend that is already taking off in USA. By creating a system where sellers are aware of the available equipment at least a year in advance, it becomes easier to find the right buyers. The final option, which was labelled the most radical, was to reuse pipelines with the purpose of transporting CO_2 instead of gas, therefore eliminating the process of removing them. All suggestions were in line with the principles of CE because, if implemented, it would result in reducing raw material extraction and improving the system in the oil & gas industry. Therefore, it may be of interest to study the impacts of different decommissioning options from an environmental perspective and how a potential change in managing the End of Life (EoL) phase of an offshore platform may affect the environment in either a negative or positive way.

The decommissioning of an offshore installation is a time and energy intensive process. According to a number of impact assessments (Breu et al., 2011; Lynch, 2015; Statoil, 2011), there are both offshore and onshore environmental impacts. These include energy use (offshore and onshore), emissions to air (vessels and onshore activities) and, discharges to sea and waste. The direct and indirect energy requirements in a decommissioning project result in a number of different gaseous emissions including carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur dioxide (SO_2), methane (CH_4) and volatile organic compounds (VOCs) (Lynch, 2015). Partial and complete platform removal may have different consequences for the environmental burden and so does each stage of the decommissioning process, which begs the question of whether improvements need to be made in this process. Furthermore, the majority of a platform's assets are sent to recycling, excluding the option of reuse or refurbishing of old equipment and materials. As a result, when a new platform is constructed, there is a need for raw materials extraction and, subsequently, the manufacturing of new equipment.

1.1 Purpose

The aim of this study was to investigate how the oil & gas industry can improve its environmental performance by implementing the circular economy principles during the decommissioning process. To achieve that, the Life Cycle Assessment (LCA) tool was used. The LCA procedure is explained in detail in Chapter 3. Additionally, the following issues were addressed:

- What are the current decommissioning techniques most commonly used in the oil and gas industry?
- How much does each decommissioning process (offshore dismantling, transport, etc.) contribute to the environmental loads?
- Are the environmental impacts reduced depending on the different EoL management options?

1.2 Limitations

The study only took into consideration the environmental impacts related to decommissioning processes. The economic and social aspects were excluded, although they are briefly discussed in Chapter 5.

The study will solely focus on the offshore oil and gas activities taking place in the North Sea. If the geographical boundaries were extended worldwide, the study would become too vast and the data would be more difficult to handle.

There are different decommissioning options depending on the regulations of a geographical area. The study considers the options of partial and complete removal, which are permitted in the North Sea under specific circumstances.

2. Theoretical background

This chapter will explain the basic theoretical concepts in order to give a better understanding of the decommissioning of offshore oil & gas platforms and its technical issues. More specifically, it will explain the decommissioning phase of such platforms and the methods used, the concept of circular economy, and the link between decommissioning and CE.

2.1 Types of offshore platforms

There are several different types of offshore oil & gas platforms. The installations can be constructed of either steel or concrete, which sit on the seabed, floating production systems, sub-sea production systems and pipelines. Each structure is unique and raises different issues in relation to its water depth, type and size (Gorman & Neilson, 1998). The oil & gas structures are illustrated in Fig. 1 along with the water depths they are usually emplaced.

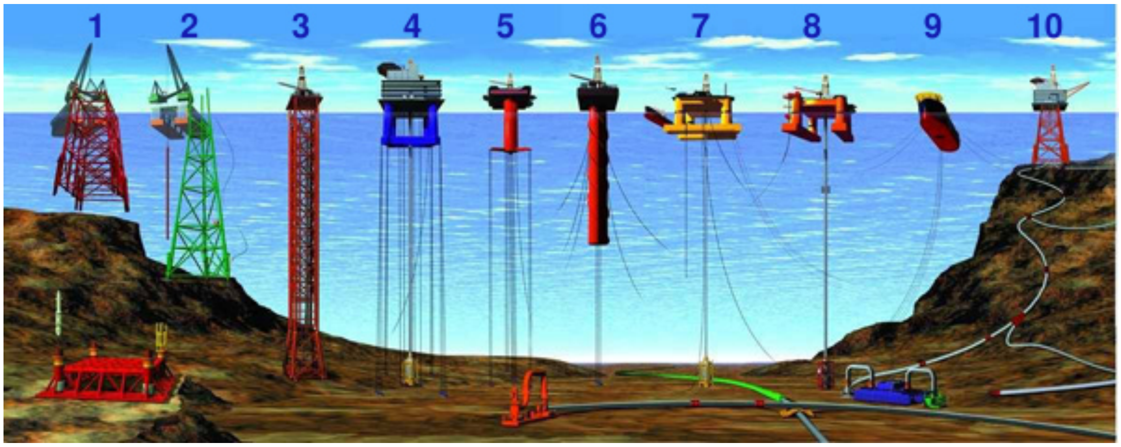

Figure 1 Types of offshore oil & gas installations (NOAA, 2006)

The majority of installations in the North Sea are either sub-sea steel installations (Fig. 1, Platform No 9) or fixed steel installations (Fig. 1, platforms No 1 and No 2). Most of the installations that have been decommissioned so far belong to the fixed steel category (OSPAR Commission, 2013).

A typical fixed steel platform consists of the following parts (Ekins et al., 2006):

- The *topsides*: the part of the platform, which remains above the surface of the sea.
- The *jacket:* the part that supports the topside. It is mainly made from tube-shaped steel.
- The *footings:* the lowest part of the jacket, which includes "pile clusters" and a drilling template.
- A pile of *drill cuttings:* situated on the bottom of the platform, it consists of drilled rock particles and fluids derived from well drilling.

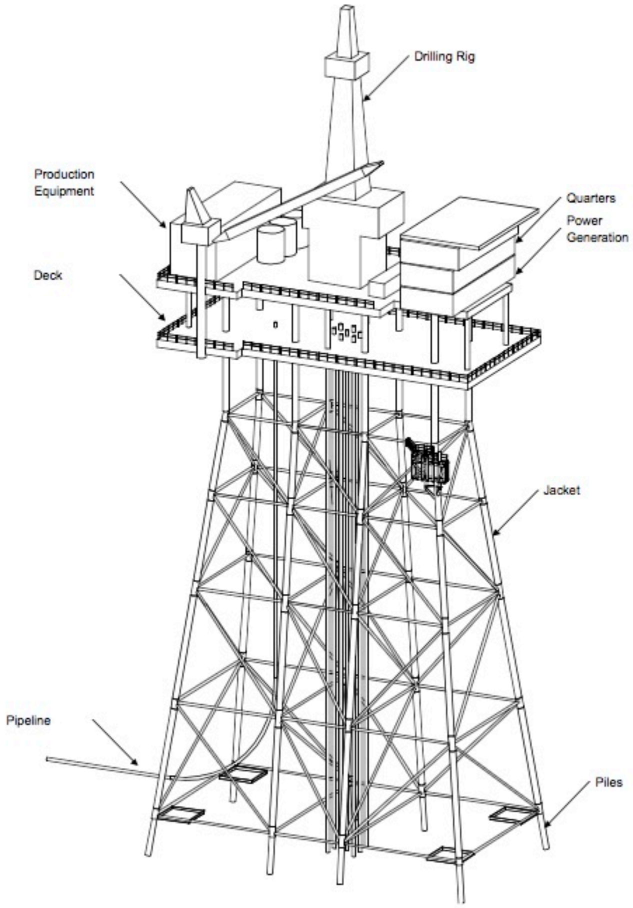

Figure 2 Generic fixed offshore platform (Thornton & Wiseman, 2000)

Due to the fact that they have their steel “legs” attached to the seafloor, these types of platforms are considered highly stable. This feature prevents the platform to be subjected to extreme movement from water and wind forces (Sadeghi, 2007). Fig. 2 offers a visual representation of a fixed steel structure.

2.2 The decommissioning process

Decommissioning is the late life stage of operations to be carried out after the Cessation of Production (CoP). More specifically, it is defined as the process by which the operator of an oil and gas installation will plan, gain approval and implement the removal, disposal or re-use of the installation when the structure has reached the end of its useful life (Jahn et al., 2008). It is generally a risky and costly operation that involves many stages before its completion. It should also be noted that every platform has unique characteristics, therefore requiring different technical approaches (Stokes, n.d.).

The oil and gas industry has been no stranger to decommissioning offshore platforms for decades but it was not until 1995 that the public became more aware and concerned about the process and its impacts. In 1991, Royal Dutch Shell decided to decommission the Brent Spar, an offshore platform of unique design for oil storage and offloading, after it ceased operation. The Brent Spar was literally a floating crude oil storage tank, a steel cylindrical structure, partially submerged with the help of concrete counterweights (Watkins & Passow, 2002). Between 1991 and 1993, Shell compiled two different decommissioning proposals. The plan was approved by the UK Department of Trade and Industry and independent scientific bodies., However, Shell was not able to gain public acceptance, mainly due to Greenpeace's extreme opposition campaign. The company faced heated rallies against its policies, the threat of a widespread boycott of its refuelling stations and a stained reputation. The decommissioning of Brent Spar was eventually completed in 1999; about 4 years after the initially planned decommissioning date. The most important mistake Shell made was that it failed to realize that decommissioning was not just a private operation, governed by national laws and regulations, but an international issue with far more stakeholders than originally engaged (Shell Int. Ltd., 2008).

The Brent Spar controversy led to a revision of the decommissioning methods used up to that point. In the 1998 Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR convention), UK and Norway joined with the rest of the European parties in accepting that the primary method for decommissioning offshore platforms would be onshore disposal (Pulsipher & Daniel IV, 2000). This agreement, along with the regulations decided at the United Nations Convention on the Law of the Sea (UNCLOS) constitute the most important legislations currently applicable in the North Sea (Hamzah, 2003). The International Maritime Organisation (IMO), a United Nations agency, is the primary global authority and sets the standards and regulations for the safety, security and environmental performance of international shipping (IMO, 2014). Based on these national and international legislations, the majority of the existing offshore installations are to be completely removed and transferred to shore for recycle, re-use or disposal. However, certain installations or parts of them can be exempt and a case-by-case approach would be performed to reach a final decision in conjunction with the local government (Osmudsen & Tveteras, 2003). Summing up, the primary decommissioning options in the North Sea are either complete or partial removal while leaving the structure in situ is only considered for concrete installations (Bureau Veritas, 2011).

There are different stages involved in the decommissioning process. Fig. 3 shows a simplified version of the stages and the timeframe.

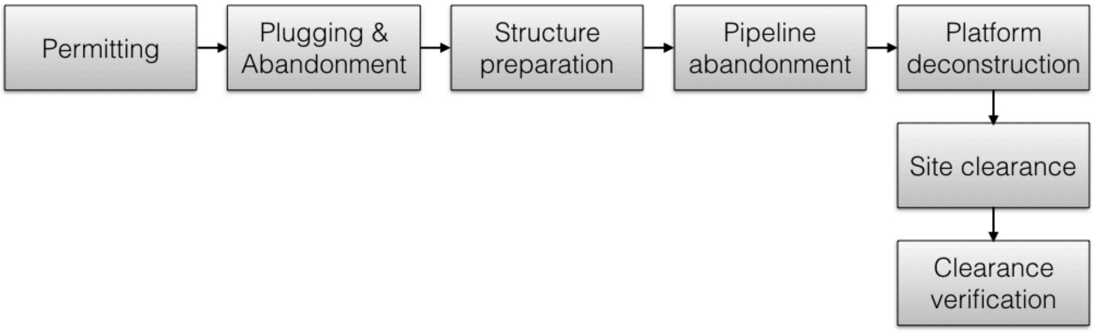

Figure 3 Primary activities in the decommissioning process (Modified from Kaiser et al., 2003)

The first steps in decommissioning are project engineering and cost assessment, followed by the acquisition of the necessary regulatory permits for well plugging and abandonment, pipeline abandonment, structure removal, and site clearance. The next step is to plug the well and prepare the facility for removal. It is quite common to bury the pipelines on site 1m below the mud line.

In addition, the modules are removed from the deck, before the deck itself is also cut and removed. Conductors and piles are cut and pulled (Kaiser et al., 2003). The topsides equipment, deck and jacket are removed and are either transported to shore by heavy lift vessels for recycling, re-use or scrap, or left in situ. Finally, the seafloor is cleared, and trawling is used to verify whether the clearance has been completed (Thornton & Wiseman, 2000).

For offshore platforms, which weigh up to 4000 tonnes and are situated in waters with depths less than 75 m, complete removal is required. If a structure was emplaced after 1998, the depth increases to 100 m (Lakhal et al., 2009). The process begins by plugging the well bores with cement, a procedure known as well abandonment. Then, the conductors[1] are separated either with the use of explosives or by cutting them off. The next stage involves the oil and gas processing equipment and the crew quarters (topsides) being cut from the jacket and removed. In the final stage, explosives are used in order to separate the piles that hold the jacket to the seabed. A cargo barge transports the jacket of the platform, or parts of it, onshore after a derrick barge[2] lifts it. The pipelines and electrical cables are either abandoned (left on the seafloor) or removed, and the seafloor is cleared (Schroeder & Love, 2004).

Partial removal is permitted for fixed steel or concrete platforms that weigh more than 4000 tonnes and are installed in waters that are deeper than 75 m. It is required to have a minimum of 55 m of clear water remaining above any platform in order to maintain safe navigation (Gibson, 2002). The process is similar to the one described above: well abandonment, and removal of topsides and conductors. However, in this case, the jacket is not completely removed and some of the remains are left in place (Schroeder & Love, 2004).

In general, there are several environmental concerns that need to be addressed during a decommissioning process. According to a simplified description by Lakhal et al. (2009), the main outputs are, among others, ship source wastes, human related wastes, releases of CO_2 and releases from metal and scraps. The Climate and Pollution Agency (2011) goes into further detail by identifying different waste types, hazardous substances (e.g. asbestos, mercury, etc.) and organic material that need to be treated during the decommissioning phases. Additionally, recent impact assessments of offshore platform removals focus on the large amounts of energy needed and its subsequent gaseous emissions.

2.3 Decommissioning in a circular economy

In recent years, the oil & gas sector has recognised the potential benefits of circular economy and has focused on identifying the opportunities by applying its principles in decommissioning of North Sea installations (Epstein et al., 2015). In the decommissioning area of the oil & gas sector, the opportunities of applying circular economy principles appear in the form of improving recycling, hence, improving the value of alloys or by reusing platform equipment. A more drastic measure is directly reusing the pipelines for carbon capture and storage (CCS) but it is still in early development stages (Benton, 2015). At the moment, recycling is already being practiced as the final stage of a platform's EoL. However, reuse is very limited in the North Sea and this is an issue that the stakeholders are looking to change. Studies are currently conducted to explore the

---

[1] Steel tubes running from the wells on the seabed to the topsides

[2] A ship with a crane attached to it, specialised in lifting heavy loads

potential re-use of different parts of a platform. A report prepared by Jee Ltd (Cumming, 2015) proposes several options for the re-use of subsea mattresses which are concrete mattresses that protect pipelines and other subsea infrastructures. In another study, a survey was put together by a technology company and distributed to oil & gas operators while an asset inventory was provided to both operators and specialist re-sellers. The goal was to assess whether old equipment and materials can be recycled, reused or restored to their original condition and used for the same purpose they were manufactured, thus reducing the resources needed to construct or extract new virgin material. This method would effectively close the "loop" of the system. The workshops between operators and asset re-sellers determined that generally 10%-15% by weight of modules/equipment could be potentially re-used (Decom North Sea et al., 2015).

2.4 Previous LCA studies on platform decommissioning

A limited number of LCA studies related to platform abandonment exist. One of the papers analysed the benefits of using LCA as an assessment and decision-making tool for the decommissioning process of offshore structures (Poremski, 1998). In it, the author argued that a screening LCA could be used as a preliminary step in order to i) identify data gaps and gather more trustworthy data, ii) to pinpoint the most significant energy and resources consumption and the contribution of emissions, iii) to select which option is the least and most favourable and, finally, iv) to suggest how the processes in decommissioning can be improved and optimised.

The first study appeared in an article by (Kerr et al., 1998). The authors took into consideration the entire scope of partial and complete platform removal options, and identified up to twelve abandonment (i.e. decommissioning) options. The primary purpose of the study was to evaluate the environmental performance of the identified options with regard to energy consumption and gaseous emissions. The results showed that there was little difference between partial and complete removal options in terms of energy consumption, although it should be noted that the lower amounts appeared mostly on the partial removal options. After estimating the overall CO_2 emissions, it was noticed that they followed a similar trend to the energy consumption, while SO_2 and NO_X emissions were significantly lower in the partial removal options due to limited marine vessel utilisation. The method appears to suggest a similar framework to that of LCA, however, the authors do not acknowledge it as a clear LCA due to certain limitations.

The most recent example was a dissertation, which clearly stated the utilisation of the LCA procedure (Ngu Pei Jia, 2013) for the evaluation of decommissioning processes. The aim was to evaluate and compare the environmental impacts of partial and complete removal, to find out the type and amount of generated waste, and to suggest alternative actions or raise any probable concerns related to offshore decommissioning. The results indicated that the energy consumption in complete removal is higher than in partial removal. Furthermore, the amounts of SO_2 and NO_X emissions were significantly lower, whereas the overall CO_2 emissions had little difference between the two options. An interesting detail was that both works mentioned above make reference to the original article of Kerr et al., determining that there have not been any further LCA studies in this particular area. The aspect missing in these studies was that not one examined the possibilities of changing the EoL phase in decommissioning and whether it would reduce the environmental impacts in any way. This was not surprising since, at the time, the potential benefits of CE in decommissioning had either not yet been researched, or the industry was not aware of these possibilities.

Although the offshore oil & gas industry has yet to establish LCA as a potentially useful tool to analyse the decommissioning process, the method is becoming more popular with other massive structures. Wallbridge et al., (Wallbridge et al., 2013) adopted the LCA procedure to estimate the potential environmental impacts related to the ongoing decommissioning of a UK nuclear power plant. Another study (Seier & Zimmermann, 2014) used the LCA to compare two scenarios with regard to a nuclear power plant decommissioning: one where the generated waste is sent to landfill and another where the waste is 100% recycled. An additional example, where the method was utilised in large structures, is an LCA study on wind turbines (Tremeac & Meunier, 2009). The authors compared two systems, a 4.5MW and a 250W wind turbine, and assessed their environmental impacts. In this case, however, they took into consideration the whole life cycle of a wind turbine, namely construction, operation and decommissioning phase.

Despite the limited number of LCA studies conducted on the subject of decommissioning, it is highly likely that it may become more widespread in the future for structures of such scale.

3. Method

Life cycle assessment (LCA) was used in this study, and this chapter will give an explanation of the procedure that is followed in an LCA and how this was applied in this study.

According to the International Organisation for Standardisation (ISO), the method of LCA was developed as a result of becoming more aware of the importance of protecting the environment and as a way to better understand and tackle impacts related to the manufacturing and consumption of products. In the introductory section of ISO 14040 it is suggested that LCA can help in: (i) improvements of products' environmental performance in numerous phases of their life cycle, (ii) decision-making in industry, government and non-governmental organisations, (iii) selecting environmental performance indicators and, (iv) marketing purposes such as making environmental claims or producing environmental product declarations (ISO 14044, 2006).

There are four different phases involved in the LCA methodology. These are the goal and scope definition, the inventory analysis, the impact assessment and, the interpretation of results (Fig. 4).

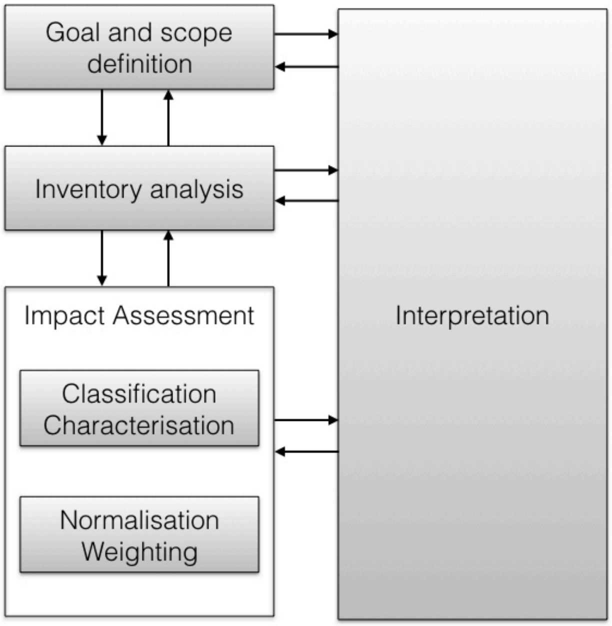

Figure 4 General framework for LCA (ISO 14044, 2006)

Goal and scope definition: This is the first step of the LCA, where the objective of the study is defined, along with its intended application and the audience that it is targeted. The scope describes the product system with regard to system boundaries and functional unit. Furthermore, the impact categories are chosen along with the method of impact assessment. It is also necessary to decide on the modelling method of a system. If the LCA aims to answer what are the total emissions from processes and material flows within a system, then it is an *attributional* LCA. On the other hand, if the LCA poses the question how the flows of a system change as a result of different decisions, it is referred as a *consequential* LCA (Curran et al., 2005; Brander et al., 2008). This step is concluded with the data quality requirements, the limitations and assumptions of the study.

The system boundaries must cover several dimensions. A product's life cycle needs to be specified, i.e. whether it begins at "cradle" (extraction of raw materials) and ends at the "grave" (final disposal of the product), whether it begins from "cradle" and ends to "gate" (excluding the use and disposal phase) or other variants. The geographical area also needs to be considered because it is possible that different phases during the life cycle occur in different places or the infrastructure may be different. Further issues that need to be taken into account are the time horizon of the study and allocation problems. The allocation problems can be addressed by creating more detailed models or by expanding the system. If allocation cannot be avoided, then partitioning which displays physical relationships between products is the next best option, and if physical relationships cannot be used, partitioning should be based on other relationships (Baumann & Tillman, 2004).

The functional unit needs to express the functions of a product. In comparative studies, it offers a way to fairly compare two different options.. ISO 14044 defines the functional unit as "the quantified performance of a product system for use as a reference unit". It also indicates that the main purpose of the functional unit is to "provide a reference to which the inputs and outputs are related" (Curran, 2012).

The *Life Cycle Inventory* (LCI) is the second step of an LCA study. It estimates the consumption of resources and the outputs of wastes and emissions associated with a product's life cycle. The various life cycle processes as well as material and energy flows are modelled accordingly in order to determine the product system and the inputs/outputs from/to the environment. Ultimately, the entire system and the inventory are normalised to the functional unit (Rebitzer et al., 2004).

The next step is *Life Cycle Impact Assessment (LCIA)*. According to Baumann & Tillman (2004), this step intends to describe the environmental impacts caused by the environmental loads quantified during the inventory analysis. This makes the results easier to understand and improves their readability and comparability. LCIA can be divided into mandatory and optional elements. The former include the impact category definition, classification, and characterisation, while the latter consists of normalisation, grouping, weighting and data quality analysis.

The final step in LCA is the *interpretation of results*. This is where the most significant issues from the results are identified and recommendations need to be made. The recommendations must be based on the final conclusions of the study. It also requires that methodological and study limitations need to be consistent when preliminary conclusions are assessed (Finkbeiner et al., 2006).

4. LCA of an offshore platform decommissioning

This chapter introduces the case study and the steps followed specifically for the case according to the LCA procedure.

4.1 Goal and scope definition

The goal of the study was to assess the environmental impacts caused by partial or complete decommissioning of an offshore platform situated in the North Sea. More specifically, the purpose of the LCA was to:

- Calculate the environmental loads of two decommissioning options and compare them to each other
- Identify which stages of decommissioning have the highest environmental impact in the system
- Assess how re-use affects the system from an environmental perspective

The results will help stakeholders decide on the decommissioning options for offshore structures that are still a subject of case-by-case decisions (parts of the platform are considered individually rather than considering the platform as a whole) as well as identify the stages in the two different decommissioning processes where improvements can be made. They can also be used in order to recognise the potential benefits of re-using various assets of a platform.

Two alternatives were considered in this study: partial and complete decommissioning. As mentioned in chapter x, the main difference between the two options is that, in the former, a platform is removed down to the beginning of the footings while in the latter, all parts composing a fixed steel structure are removed. In both cases, a hypothesis was made, wherein re-using platform assets was introduced. More concretely, it was hypothesized that the environmental performance of the system would change if reuse was involved in the final stages of decommissioning.

4.1.1 Functional unit

The definition of the functional unit is one of the most important steps in the LCA. In this study, it was decided that the most appropriate one would be "decommissioning of one offshore fixed steel platform". This is in line with previous LCA studies, in which the to-be-decommissioned structure was used as the functional unit. The reference flow was calculated based on the amount of materials comprising a fixed steel structure, i.e. 40000 tonnes of material, of which about 97% is steel, 2% is aluminium and the remaining percentage is other metals and non-metals (Ekins et al., 2006).

4.1.2 System description

The flowchart representing complete removal is illustrated in Fig. 5. It was designed based on the alternatives proposed for the decommissioning of the North West Hutton platform, a typical fixed steel structure situated on the UKCS, which reached its CoP in 2003 (British Petroleum, 2006). Since the main difference between partial and complete decommissioning is whether footings will be left *in situ* or not, it was deemed unnecessary to create an additional flowchart. If the flowchart was designed, then the "footings dismantling" box would be excluded from the system. The system was limited to the activities involving the decommissioning process, as indicated by the dotted square. All steps outside it were not taken into consideration during the study.

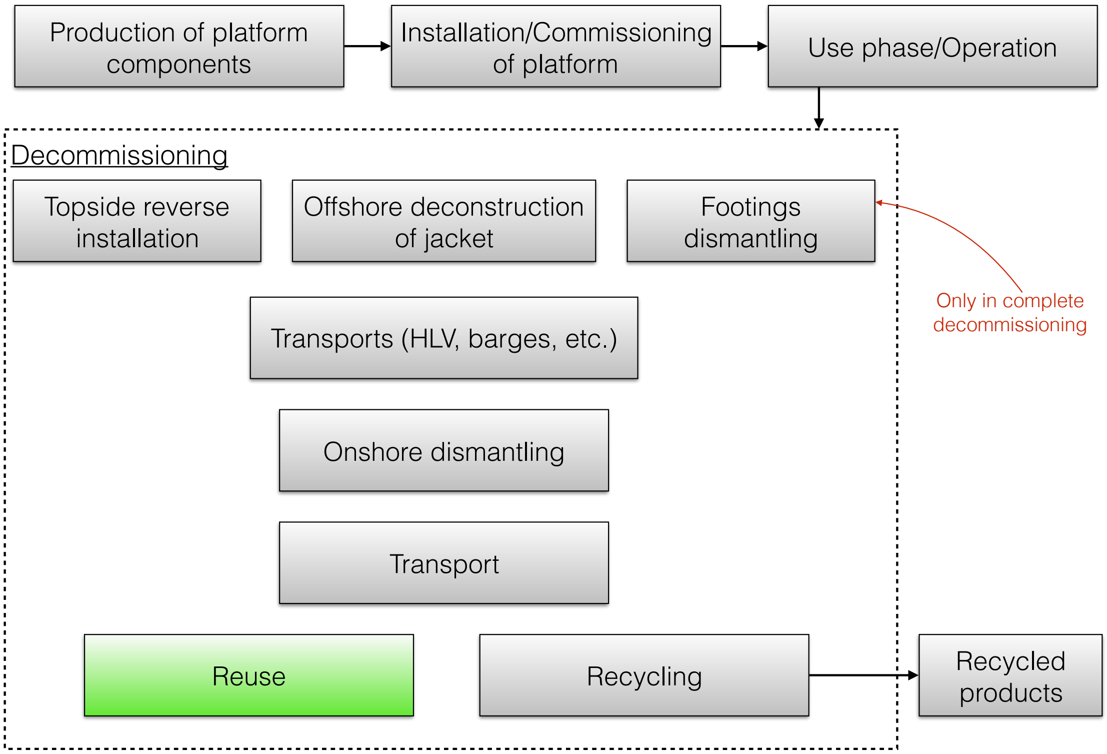

Figure 5 Flowchart for complete decommissioning. The green painted box indicates the scenario of re-use.

The decommissioning operations begin with the dismantling of the topsides by *reverse installation*, i.e. pieces are removed piece by piece similar to how they were initially installed. First, all piping, electrical wiring and other services that connect the platform systems between each module are cut and separated. Then, the structures are separated from each other in order for them to be lifted individually. The operation requires the use of diamond wire saws. The modules are sequentially removed by heavy lift vessels (HLV) and securely positioned either on the vessels or on transport barges, which will transport them to the arranged dismantling area.

The platform's jacket is removed with the method of offshore deconstruction. The operation begins from the top of the jacket and continues down to the beginning of the footings. Several lifts and cuts need to be made, and the severed sections are then lifted by HLVs, positioned on a barge and transported onshore.

The footings are removed in a similar way to the jacket by cutting the legs into pieces and lifting them. Explosives can be used as an engineering solution to making holes for drainage. In the case of partial removal, as mentioned earlier, this stage is excluded and the footings remain on the seabed. All the pieces collected from the platform are transported to shore, where they are further reprocessed and sent to either recycling or landfill.

It is in that last stage of the system, where the reuse scenario was added. Instead of recycling or disposing all parts of the platform, the study assumed that certain assets can be reused either by installing them in other platforms or for completely different purposes. Subsequently, the EoL of the platform changed to the options of recycling and reuse.

4.1.3 System boundaries

The geographical region was the UKCS in the North Sea including the United Kingdom for the onshore dismantling. It is not exactly accurate to state the study as a cradle-to-grave approach since decommissioning is a process within the life cycle of the platform. Therefore, the boundaries were not defined as it is conventionally done in other LCAs. The LCA adopted an attributional modelling, which aimed to identify and describe the emissions from the different processes and material flows within the chosen system. The system boundaries included the topside reverse installation removal, the offshore deconstruction of the jacket, the footings dismantling (only for complete decommissioning), the onshore dismantling, the recycling of waste, and the transports taking place in between those stages. It should be noted that there is an amount of waste going to landfill. However, it was assumed that the amount was too small to be significant and the data too limited so it was not included in the assessment. Following the comparison between complete and partial decommissioning, the LCA adopted more of a consequential nature because the goal was to identify how the emissions would change if equipment from the platform (more specifically the material used in equipment) were reused instead of being sent to recycling. The system boundaries also changed in order to include the reuse scenario during the EoL phase. The extraction of raw materials for construction, the installation and the use/operation phase of the platform are excluded. The manufacturing of heavy machinery used in decommissioning and means of transport are also excluded. Transportation of personnel from and to the platform was also not taken into account. The construction of the facilities handling the onshore dismantling was not considered. Due to a lack of data, the manufacturing of potentially reused equipment was excluded. Alternatively, the study opted to consider the amount of material used for the construction of that equipment, therefore, taking into account the extraction and processing of the materials.

The temporal boundaries of the study were defined to be 100 years. A decommissioning process can take several years to reach full completion. Combined with the fact that the consequences of various pollutants may appear long after the end of the project, this time horizon was considered to be appropriate for a comprehensive and accurate assessment.

4.1.4 Impact categories

The CML 2002 characterisation method was used for the impact assessment. The impact categories chosen for the study were:

- *Global Warming Potential:*

  One of the main gaseous emissions involved in decommissioning is CO_2, which has significant climate impacts. To set that into context, the Miller Decommissioning Programme report (British Petroleum, 2006) compared the amount of CO_2 emissions released during different activities in decommissioning to the average annual emissions of UK households. For example, a topside reverse installation removal would amount to 38.560 tonnes of CO_2 released by HLVs, which equals to 0,15% of emissions from UK households.

- *Eutrophication:* Another impact category considered relevant for the study was eutrophication; the enrichment of water by phosphorus and nitrogen. Fuel burning emits NO_X into the atmosphere, which are later resettled to soil and water.

- *Acidification:* A decommissioning project requires a number of transportation vessels, which have to make several trips to and from the platform. When the onshore dismantling occurs, heavy machinery need electricity to operate. The burning of fuels releases pollutants such as SO_2 and NO_X, which contribute significantly to acidification.

4.1.5 Data quality requirements

The data used for carrying out this study were collected from different sources. Common processes were found in the EcoInvent 3.1 database. However, due to the fact that decommissioning has not been researched extensively in LCA studies, several processes could not be found in the database. In such cases, data were taken from other literature studies or company reports. Data for steel recycling were requested and retrieved from the World Steel Association and the International Aluminium Institute, respectively.

The results of the study are directly affected by the quality of data. Baumann and Tillman (2004) suggest three terms for evaluating data and assessing the results; relevance, reliability and accessibility. This subject will be further discussed later in the report.

4.1.6 Assumptions and limitations

The following assumptions had to be made in order to conclude the study:

- It was assumed that almost 90% of the steel material from the platform is recycled during the initial comparison of the two decommissioning options (Oil & Gas UK, 2012).
- It was assumed that 33 crane lifts are needed for the reverse installation of the module, with a maximum weight limit of 600T each.
- The cutting equipment was assumed to make about 250 cuts to fully remove the jacket of the platform (British Petroleum, 2006).
- For the reuse scenario, it was assumed that about 20 tonnes of aluminium (helideck) and 2000 tonnes of steel (equipment) could be recovered from the topside (British Petroleum, 2006), which amounted to about 10% of the total amount of topside material in the platform.
- The recycling facilities were assumed to be situated close the dismantling facility, therefore the emissions were not considered significant.
- The HLV has to make at least 3 round trips from land to the platform and vice versa.
- The transport barge has to make at least 5 round trips in order to transport all the pieces of the platform
- The distance between the platform and the onshore dismantling facility is assumed to be 850 km.
- Offshore equipment are assumed to run on diesel while for onshore equipment, the electricity production mix of Great Britain was used.
- The machinery used for the dismantling of the platform is limited to diamond wire saws and lifting cranes.

- Due to limited information on the material going to landfill and the fact that it amounted to about 2% of the total EoL phase, emissions were limited to recycling and reuse.
- Transportation was limited to sea transport with the use of HLV and transport barges.

4.2 Inventory Analysis

To facilitate the calculations in the LCI, the decommissioning process was divided into several stages. These were: topside dismantling, jacket dismantling, footings dismantling, recycling and re-use. The following paragraphs display the inputs and most important outputs of these stages. Tables 1 and 2 compare the aggregated data from offshore and onshore dismantling for complete and partial decommissioning, respectively.

Table 1 Inputs/Outputs during offshore dismantling for complete and partial decommissioning

	Complete		Partial	
Input	***Amount***	***Unit***	***Amount***	***Unit***
Cutting wire saw use	2,58E+04	MJ	2,43E+04	MJ
Cranes & Lifts (HLV) use	5,66E+07	MJ	5,57E+07	MJ
Explosives use	40	kg	-	-
Output				
CO2	4,13E+06	kg	3,99E+06	kg
SO2	1,34E+03	kg	1,29E+03	kg
NOx	5,83E+04	kg	5,64E+04	kg
CH4	2,12E+02	kg	2,05E+02	kg

Table 2 Inputs/Outputs during onshore dismantling for complete and partial decommissioning

	Complete		Partial	
Input	***Amount***	***Unit***	***Amount***	***Unit***
Crane use	6,29E+06	MJ	4,54E+06	MJ
Cutting equipment use	4,52E+05	MJ	3,01E+05	MJ
Output				
CO2	6,21E+05	kg	4,46E+05	kg
SO2	2,06E+03	kg	1,48E+03	kg
NOx	1,40E+03	kg	1,01E+03	kg
CH4	2,22E+03	kg	1,59E+03	kg

The most critical inputs in both offshore and onshore dismantling are heavy machinery and cutting equipment. The amount of energy used in HLVs was calculated based on their lifting capacity and energy consumption according to MacGregor company (2015). A similar method was applied for calculating the energy use of cutting equipment. Hydraulic requirements were calculated by using the data from a company providing diamond wire saw (MacTech Offshore, n.d.). Only some of the major discharges were presented in the outputs and were based on UK energy statistics (Department of Energy and Climate Change, 2014) and data collected from EcoInvent, namely processes of [diesel, burned in building machine, alloc. default, U] and .[GB electricity mix].

The main materials processed during the onshore dismantling were steel and aluminium, which were then sent to recycling facilities. The inputs and outputs of these facilities were retrieved from the International Aluminium Institute report (Klöpffer & Frischknecht, 2013) and via email from the World Steel Association (Winslow et al., 2012). Subsequently, they were normalised to the functional unit (see Table 3).

Table 3 Inputs/Outputs from steel and aluminium recycling

	Complete		Partial	
Input	***Amount***	***Unit***	***Amount***	***Unit***
Steel scrap	3,90E+07	kg	2,90E+07	kg
Aluminium	8,00E+05	kg	8,00E+05	kg
Electricity	1,15E+05	kwh	1,15E+05	kwh
Output				
CO2	5,06E+07	kg	3,78E+07	kg
SO2	9,23E+04	kg	6,91E+04	kg
NOx	8,62E+04	kg	6,43E+04	kg

For the reuse scenario, the data were collected with regard to the materials that comprise several assets of an offshore platform. According to the Hutton assessment (2006), the main materials that can be found in potentially reusable equipment are aluminium and steel. Table 4 shows the emissions that can be avoided if these materials are not extracted and used in the manufacturing of certain equipment. It can be observed that the emissions in the reuse scenario are the same in both the complete and partial decommissioning. This is justified by the fact that the reuse materials come from the topsides, which in both alternatives are fully decommissioned on shore.

Table 4 Emissions avoided when reuse takes place

Emissions	Amount	Unit
CO2	5,66E+06	kg
SO2	4,82E+03	kg
NOx	3,57E+03	kg
CH4	2,86E+02	kg

Important emissions were also calculated from transportation. The main means of transport used are HLV and transport barge and both were assumed to operate on diesel fuel. Tables 5 and 6 show the emissions from transporting the platform pieces to the dismantling facility for complete and partial removal, respectively.

Table 5 Emissions from transportation in complete removal

Emissions	Amount	Unit
CO2	9,57E+06	kg
SO2	1,61E+05	kg
NOx	2,21E+05	kg

Table 6 Emissions from transportation in partial removal

Emissions	Amount	Unit
CO2	7,32E+06	kg
SO2	1,23E+05	kg
NOx	1,70E+05	kg

4.3 Life Cycle Impact Assessment

This part of the study dealt with the environmental impacts, as described in the goal and scope definition. The different scenarios related to the offshore platform decommissioning were compared and the results of the study were interpreted. The inventory results were assigned and sorted to the selected impact categories. Fig. 6 to 8 illustrate the results from the comparative LCA study between complete and partial decommissioning. The study also addressed how much the several stages of decommissioning contributed to the total impacts. This allowed for better understanding of the system and for identifying the main culprits.

The results showed that partial decommissioning has lower environmental impact than complete decommissioning. This can be explained by the fact that the footings of the platform remain offshore, and therefore several technical processes (cutting wire saw, cranes, explosives, etc.) are excluded. Furthermore, transportation emissions are also reduced because transport barge trips to and from the platform are cut down.

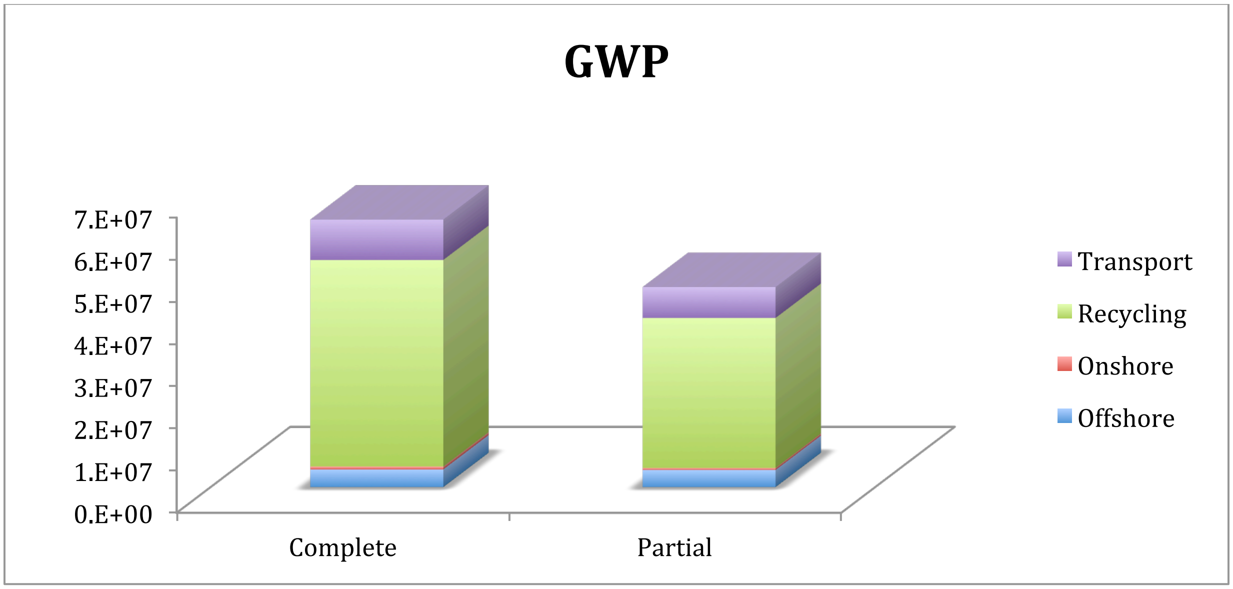

Figure 6 Contributions of different processes in complete and partial decommissioning for kgCO2-eq

The main contributor for the GWP appears to be recycling. This does not necessarily come as a surprise considering the massive weight of materials that are recycled.. The recycling of metals follows several steps and it is an energy intensive process. It begins with the pre-processing of metals, during which time the metals are sorted out, dismantled and physically or chemically separated. Subsequently, the materials are sent to smelter or other thermochemical facilities for the end-processing (Reck & Graedel, 2012).

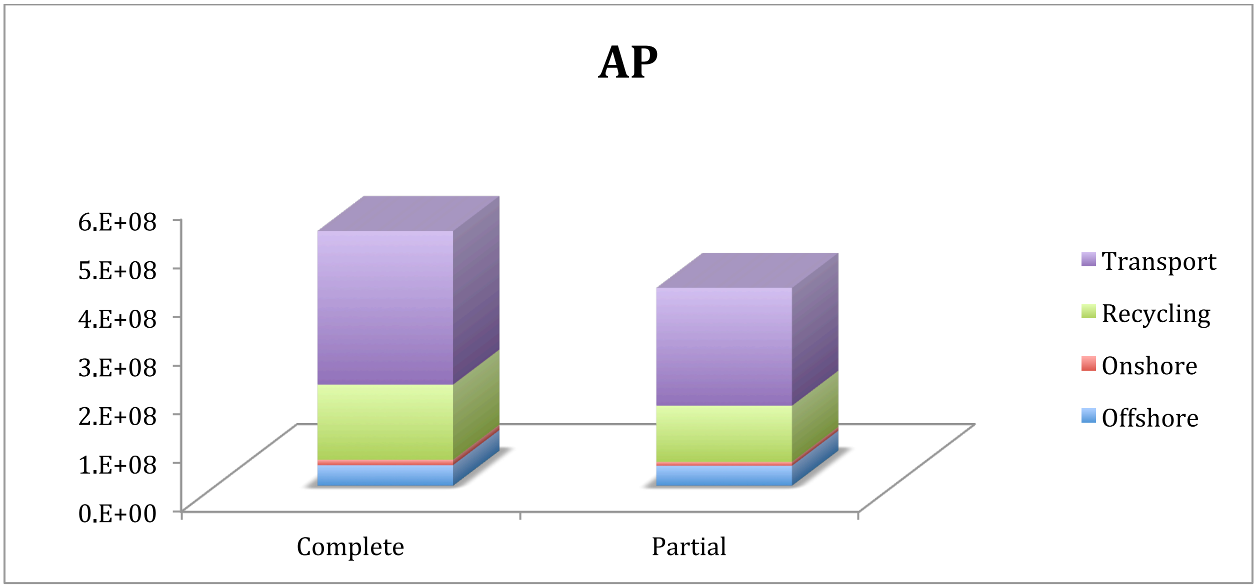

Figure 7 Contributions of different processes in complete and partial decommissioning for gSO_2-eq

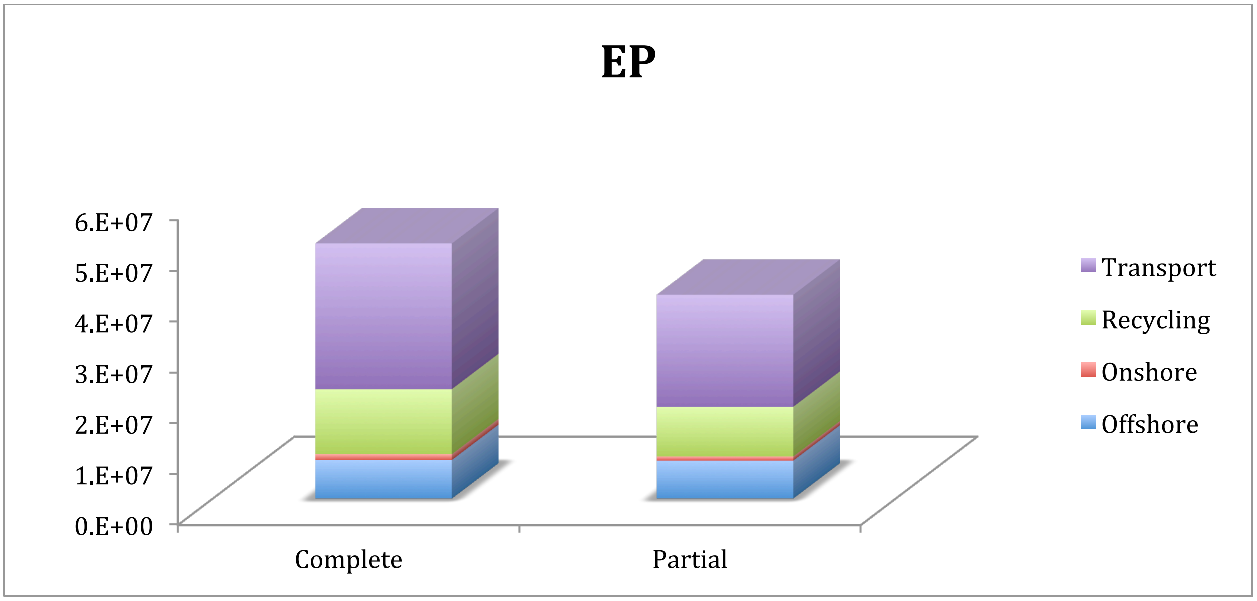

Figure 8 Contributions of different processes in complete and partial decommissioning for gPO_4-eq

In both AP and EP, transportation has the largest impact. The vessels used for transferring the dismantled parts of the platform, travel long distances and carry tonnes of materials. As a result, they burn significant amounts of fuel, releasing harmful gases in the process.

Summarising the results from the processes, it can be concluded that the main contributors in all impact categories are recycling and transport, which suggests that improvements need to be made in this area. If reuse turns into a common alternative, then it may reduce the emissions from recycling. Furthermore, if different dismantling methods become technologically viable and if more energy efficient transport barges are introduced, transportation emissions may also be reduced.

As previously mentioned, one of the main goals of the study was to identify whether any change would occur in the system when certain assets of the platform were reused. Figures 9 to 11 show the results of these calculations when 10% of the topside's materials is reused.

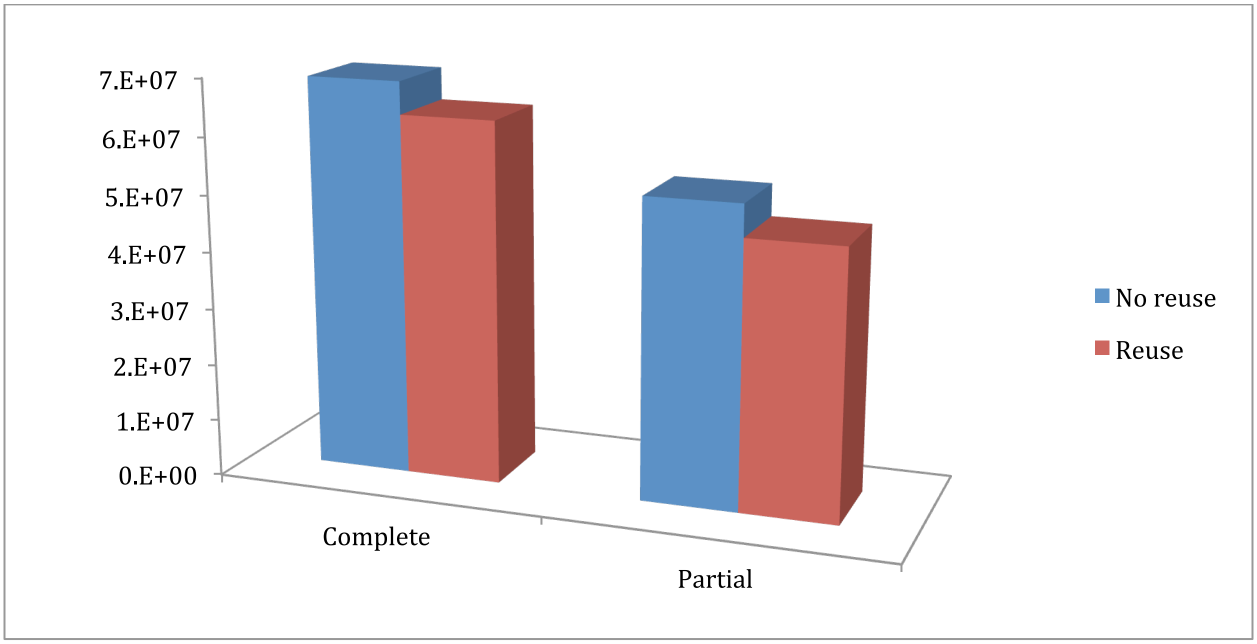

Figure 9 Comparison of decommissioning options with and without reuse for GWP in kgCO_2-eq.

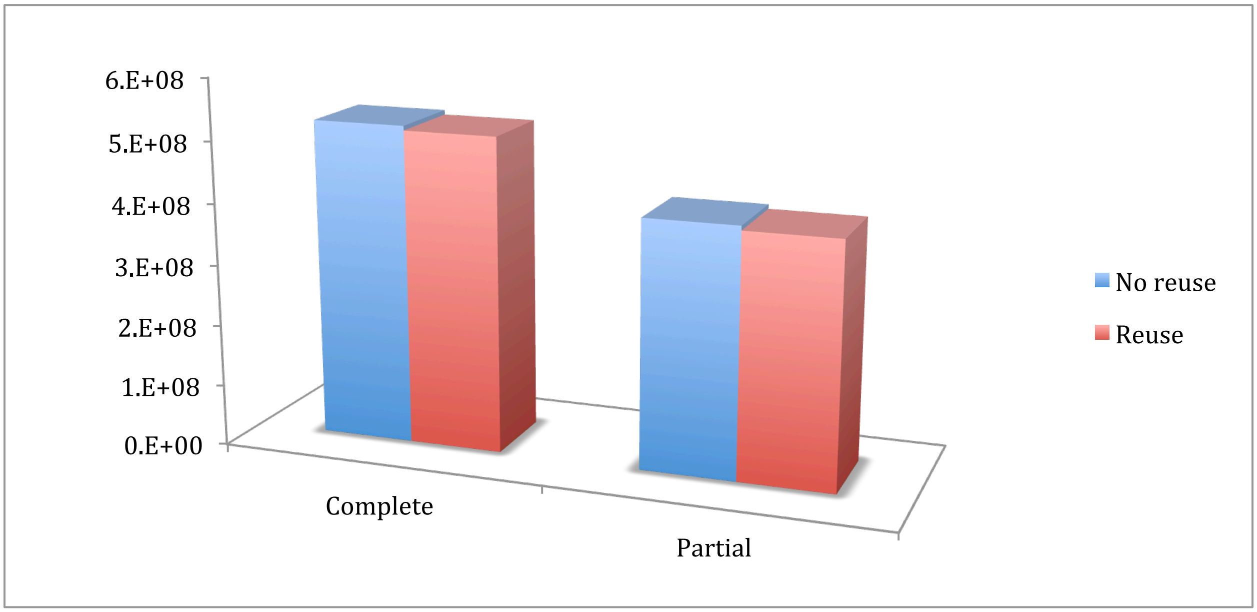

Figure 10 Comparison of decommissioning options without and with reuse for AP in gSO_2-eq.

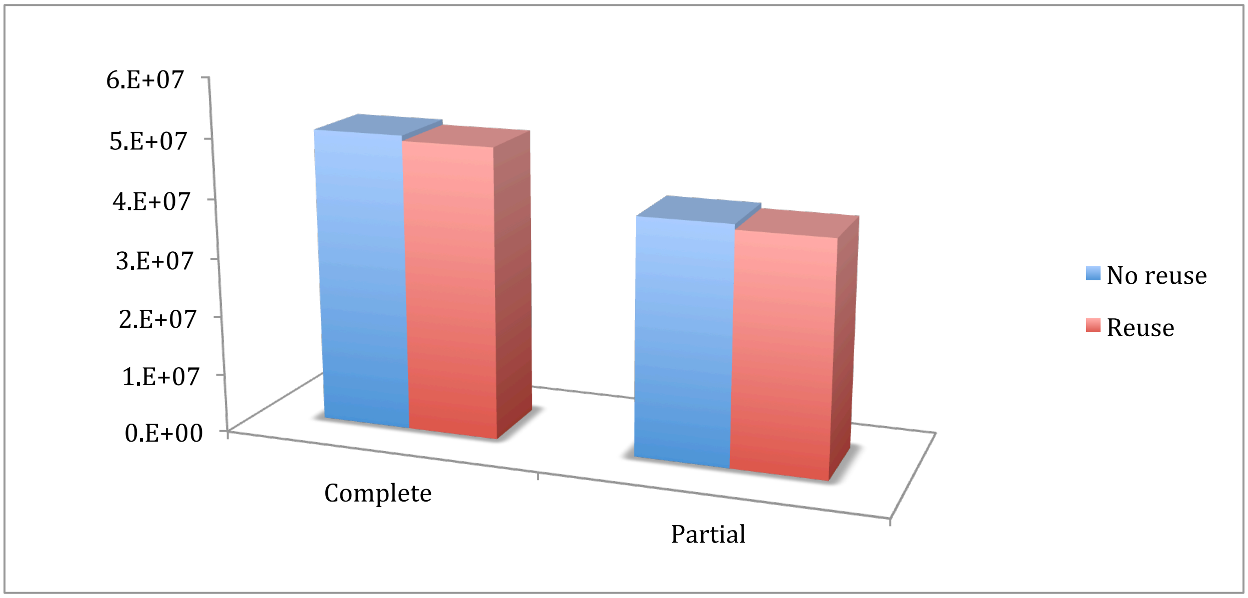

Figure 11 Comparison of decommissioning options without and with reuse for EP in gPO_4-eq.

The results showed that the potential option of reusing assets of the platform results in a decrease in all impact categories. The most significant difference appeared in the GWP, where the impact was reduced by 8,2% in complete decommissioning, and by 10,8% in partial decommissioning. This can be explained by the fact that the amount of materials heading to recycling is reduced since some of the platform's assets are reused. In the AP and the EP, the difference between the no reuse and reuse scenario was smaller. The former was reduced by 1,3% in complete removal and by about 2% in partial removal while the latter experienced a decrease of about 1,8% and of 2,25% in complete and partial decommissioning, respectively. It was not very surprising that both AP and EP did not show a significant change. According to figures 7 and 8, the process that contributed the most in those categories was transportation, which was not necessarily affected when the reuse scenario was introduced. The equipment/materials still needed to be transported to shore, therefore, emissions from transportation could not be avoided. Although the percentages were smaller than that of GWP, and small in general, it was nonetheless interesting to see that a 10% reuse introduced a small reduction in the environmental impacts of the decommissioning process.

4.4 Sensitivity analysis

The percentage of reuse considered was around 10% of the total waste management options of topsides. A sensitivity analysis was performed in order to observe at which point reuse would actually make a difference in the impact assessment results. In order to see how changes influenced the impacts of the system, different percentages were considered for the reuse. Figures 12, 13 and 14 show the results with regard to the three impact categories when 25% and 40% reuse was introduced (including the 10% reuse baseline scenario). The reason that these percentages were chosen was because it is highly unlikely that reuse can go beyond that point.

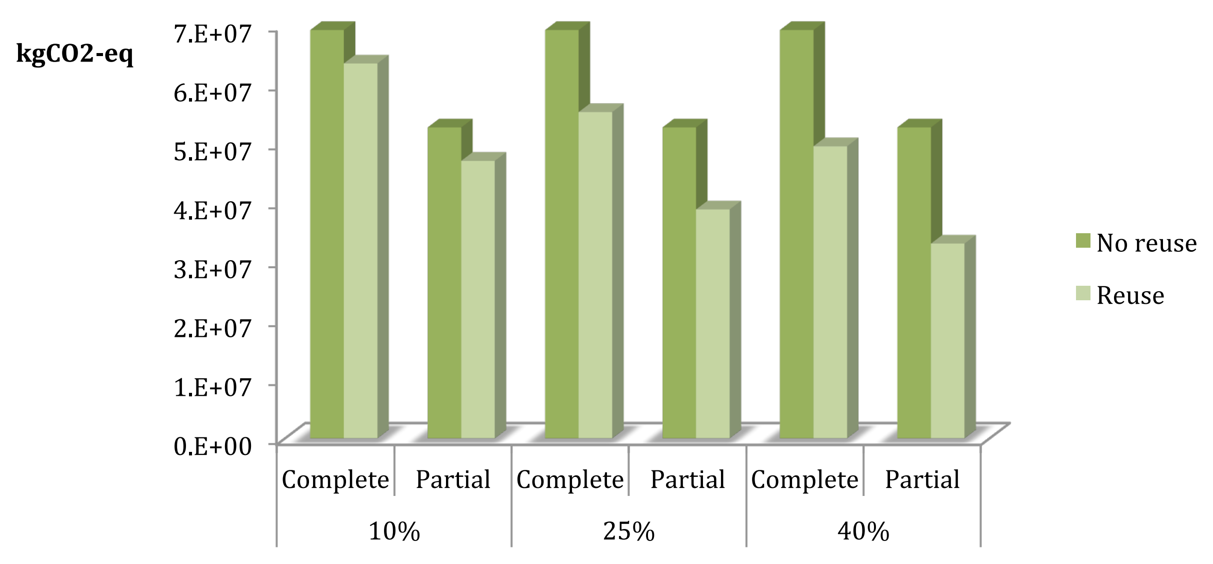

Figure 12 Sensitivity analysis for the GWP with 10%, 25% and 40% reuse.

It can be observed that with an increase to 25% of the total topside material, the difference between the scenarios was slightly increased. The GWP in complete and partial decommissioning was decreased by about 20% and 26%, respectively. When reuse was increased to 40%, the GWP was reduced by 28% and 37% for the two decommissioning options.

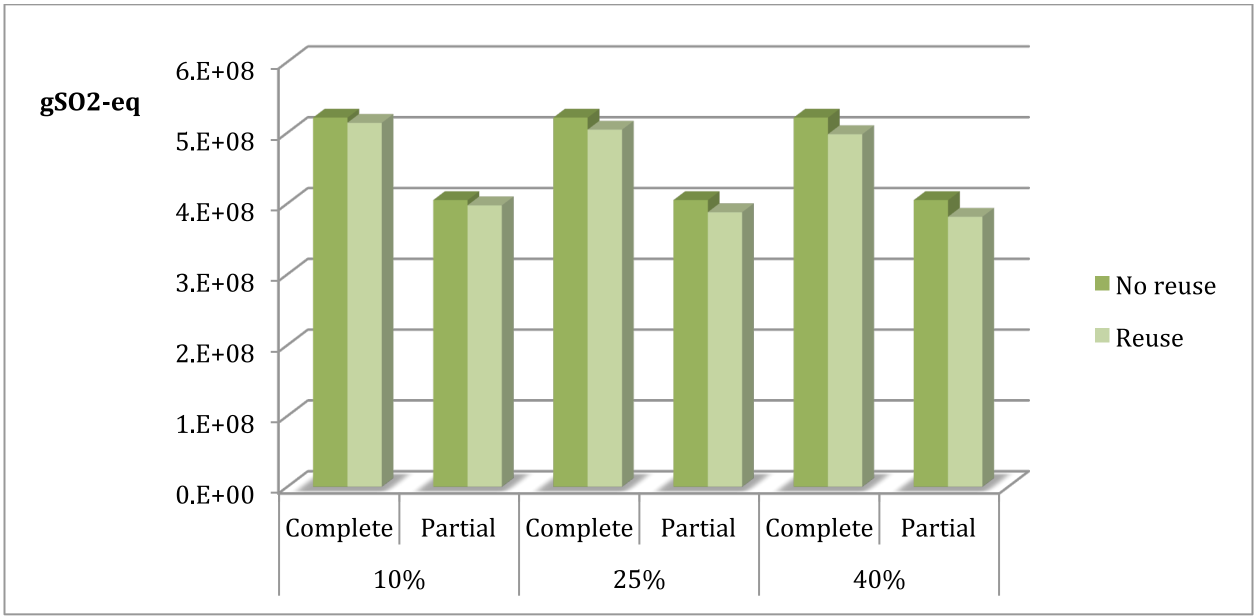

Figure 13 Sensitivity analysis for the AP with 10%, 25% and 40% reuse.

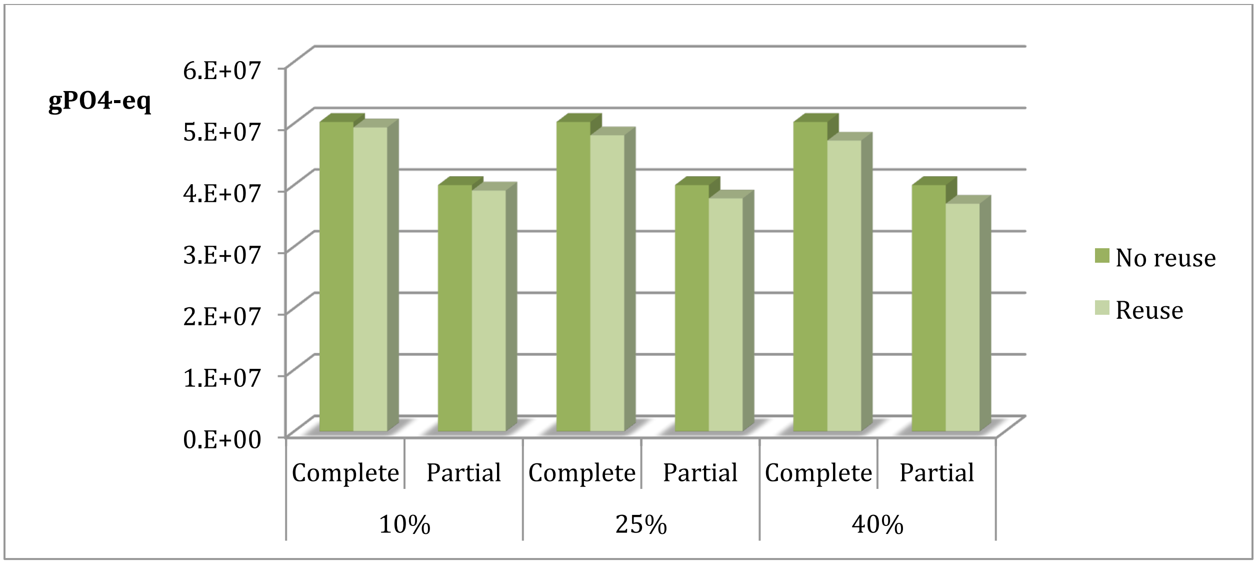

Figure 14 Sensitivity analysis for the EP with 10%, 25% and 40% reuse.

The sensitivity analysis also revealed that the AP and EP had a steady but still rather small decrease. Figure 13 showed that for the 25% reuse, the AP had a decrease of about 4% in both complete and partial decommissioning. For the 40% reuse scenario, the differences were reduced by 4,5% and 6% for the decommissioning options. In Fig. 14, which illustrated the sensitivity analysis for the EP, the results concerning the 25% reuse scenario showed that there was a 4,4% reduction in complete removal while in the case of partial removal, it was decreased by 5,5%. The 40% reuse indicated a reduction too. In complete decommissioning, there was a 6% reduction from the original scenario while partial decommissioning was reduced by almost 8%.

It can be summarised that the most notable change was identified in the GWP. As it was previously mentioned, the reason for that was the contribution of emissions from recycling during the decommissioning process. The AP and EP results showed an improvement although the percentages remained rather low due the necessity of marine vessel utilisation. The following chapter discusses, among other things, suggestions for optimising the transportation, which may subsequently result in increasing these percentages.

5. Discussion

The purpose of the study was to compare two alternatives options of decommissioning and assessing what would change in the system when reuse of the platform's topside assets is economically feasible. The study would have been significantly improved if more data were available and the research on applications of circular economy in decommissioning was more advanced. Nonetheless, it indicates that there are issues that need to be addressed in terms of transparency in the decommissioning process as well as improvements in the techniques that are currently used for dismantling the different parts of a platform.

In studies such as this one, it is rather difficult to be completely accurate. The boundaries that need to be set for the system will ultimately exclude other information and data availability is already limited in the decommissioning process. The sensitivity analysis provides some reassurance for the number of uncertainties surrounding the study. After its completion, the study was compared to previous similar studies. It must be remarked that it is not easy to compare such studies since they usually have different boundaries, and deal with limitations in a different manner. For the comparative part of this study, the results were in agreement with both previous studies (Kerr et al., 1998; Ngu Pei Jia, 2013) in that complete decommissioning has higher environmental impacts than partial decommissioning. Unfortunately, there exists no LCA study, which assesses the potential changes in the decommissioning process for a reuse scenario and consequent changes in environmental impact. Therefore no comparisons could be made.

According to the results, the processes that contributed the most to the environmental impacts were recycling and transportation due to a high amount of energy consumption. One way of reducing recycling emissions is to increase reuse in decommissioning. This will limit the amount of materials that need reprocessing, hence, it will reduce the energy consumption in the recycling facilities. The utilisation of marine vessels also needs improvement, and it can be accomplished from different perspectives. One option is to improve energy efficiency through design alterations. That would include the reduction of ship energy requirements, the improvement in efficiency of transmitters and converters, and the use of more renewable sources. The alternative option would be to improve energy efficiency through operational changes (Brynolf et al., 2016).

Furthermore, the results of the LCA study show that there are environmental benefits in reusing a platform's assets rather than sending all materials to recycling (or landfill). However, there are several issues that need to be addressed before it becomes a common practice during the EoL phase of a platform. The oil & gas industry is a risk-averse sector and rather reluctant to reuse old equipment. Operators do not consider old equipment as reliable as new equipment, and worry about the increase in costs from maintenance and lower efficiency. Another concern is that older equipment may not be consistent to the requirements imposed by modern regulations. Additionally, reused equipment may be unfit for the final design of a new platform, causing issues with the equipment layout and, it may not be as effective and functional as new ones. Further issues include the alternative removal methods that need to be adopted in order to remove part from the platform safely and in good condition. It is also fair to note that most of the platforms that will be decommissioned in the near future are quite old, and when they were originally designed there was no reuse in mind, making it more difficult to find recoverable equipment.

To improve the amount of components and materials re-used, the RSA Great Recovery & Zero Waste Scotland Program (Epstein et al., 2015) proposed a generic framework. The first step is a pre-landing audit that will create a detailed inventory of materials, components and equipment and offer an early indication of the potential recoveries before the CoP. After the CoP, the resources will be removed from the platform and transferred to shore where they will be assessed. The assessment method will reduce uncertainty among oil & gas operators and they may become more willing to buy used equipment. The next steps of the framework include decontamination and refurbishing, followed by testing, certification and warranty. Finally, all resources will be able to hit the markets either through specialist resellers or companies specialised in new components.

Reuse does not apply only to the oil & gas industry. Nuclear power plants have also been considered as a potential source of reused components. However, it was a challenge to characterise the material and get legislative approval to promote the options. One example, where operators found a solution to reuse material, was at the National Conversion Pilot Project in which scrap was converted to wastes casks (IAEA, 2000). Other sectors have realised economic and environmental benefits of adjusting their business model to the CE principles. From IT-companies and online portals to packaging and clothing companies, there is a wide range where reuse has been applied and resulted in reduced resource consumption, lower emissions and use of existing assets (Ovaska et al., 2016).

The application of the CE principles in the decommissioning process offers not only environmental but economic and social benefits as well. The reports (Decom North Sea et al., 2015; Epstein et al., 2015) imply that the oil & gas industry can save more money from reusing equipment rather than from disposing it. Furthermore, more job opportunities are created due to the need of extra personnel for the removal and refurbishing of the resources. It has also been demonstrated that equipment that is no longer useful to the operators may find good use for a different purpose. That was the case with a solar-powered mechanical pump, which was donated to a village in Africa (Decom North Sea et al., 2015).

More transparency is necessary in the decommissioning process. It would offer more credibility to a study and it would assist in the process of comparing different studies. The availability of data is very limited, which makes it difficult for studies similar to this one to get more assertive results. There is also a lack of decommissioning-related processes in LCA software, which further reaffirms the problem of data collection. A detailed and accurate account of inputs and outputs related to decommissioning would facilitate forthcoming LCA studies on this subject and allow for a better understanding of the multiple stages involved in the process. The lack of data in such a study led to a number of assumptions in order to complete the study, which in turn created an uncertainty about the results. If current studies on reuse scenario continue to hold public and industrial interest, then future research on the reuse scenario would bring interesting results. Years before, in the Gulf of Mexico, the whole topside was removed from an old platform and, after refurbishing, it was reinstalled to a new offshore platform (Schroeder & Love, 2004).

6. Conclusions

According to this study, partial decommissioning is a better option from an environmental perspective than complete decommissioning. In all impact categories, the results showed that the former performed better than the latter, mainly because a lower amount of material needed to be removed from the platform. This resulted in lower energy consumption and reduced transportation.

The processes that contributed the most to GWP, AP and EP were recycling and transport while onshore and offshore dismantling scored much lower with regard to the total amount. The results indicated that recycling, and transporting such a high amount of materials, was an energy intensive process.

The pairing of CE and the decommissioning process proved to be an interesting idea. The reuse scenario produced significant changes to the environmental impacts of both partial and complete decommissioning. The largest difference was shown in the GWP as a result of a reduction in material recycling and, consequently energy use.. A sensitivity analysis suggested that as the percentage of the reuse of a platform's components increases, the difference between no reuse and reuse scenario increases.

Bibliography

Andrews, D. (2015) The circular economy, design thinking and education for sustainability. *Local Economy*, 30 (3), pp.305–315.

Baumann, H. & Tillman, A.-M. (2004) *The Hitch Hiker's Guide to LCA*. Lund, Studentlitteratur AB.

Benton, D. (2015) *Circular Economy Scotland*. London.

Brander, M., Tipper, R., Hutchison, C. & Davis, G. (2008) Consequential and attributional approaches to LCA: a Guide to policy makers with specific reference to greenhouse gas LCA of biofuels. *Econometrica Press*, 44 (April), pp.1–14.

Breu, F., Guggenbichler, S. & Wollmann, J. (2011) *Miller Decommissioning Programme*. Available from: <http://medcontent.metapress.com/index/A65RM03P4874243N.pdf>.

British Petroleum (2006) *North West Hutton Decommissioning Programme*.

Brynolf, S., Baldi, F. & Johnson, H. (2016) Energy Efficiency and Fuel Changes to Reduce Environmental Impacts. In: *Shipping and the Environment: Improving environmental performance in marine transportation*. Gothenburg, Springer Berlin Heidelberg.

Bureau Veritas (2011) *Decommissioning on the UK Continental Shelf - an overview of regulations*.

Climate and Pollution Agency (2011) *Decommissioning of offshore installations*. Oslo.

Cumming, D. (2015) *Mattress Solutions*.

Curran, M.A. (2012) *Life Cycle Assessment Handbook: A Guide for Environmentally Sustainable Products*. 1st ed. Wiley. Available from: <http://ebookcentral.proquest.com/lib/chalmers/reader.action?docID=1047617>.

Curran, M.A., Mann, M. & Norris, G. (2005) The international workshop on electricity data for life cycle inventories. *Journal of Cleaner Production*, 13 (8), pp.853–862.

Decom North Sea, Zero Waste Scotland & ABB (2015) *Offshore oil and gas decommissioning*.

Department of Energy and Climate Change (2014) *UK Energy Statistics – 2013 provisional data*.

Ekins, P., Vanner, R. & Firebrace, J. (2006) Decommissioning of offshore oil and gas facilities: A comparative assessment of different scenarios. *Journal of Environmental Management*, 79 (4), pp.420–438.

Ellen MacArthur Foundation, McKinsey Center for Business and Environment & SUN (Stiftungsfonds für Umweltökonomie und Nachhaltigkeit) (2015) *Growth within: a circular economy vision for a competitive europe*.

Epstein, D., Jones, K., McCann, E., Thomas, S. & Carris, J. (2015) *The RSA Great Recovery & Zero Waste Scotland Programme*.

Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K. & Klüppel, H.-J. (2006) The New International Standards for Life Cycle Assessment: ISO 14040 and ISO 14044. *The International Journal of Life Cycle Assessment*, 11 (2), pp.80–85.

Gibson, G. (2002) The Decommissioning of Offshore Oil and Gas Installations : A Review of Current Legislation , Financial Regimes and the Opportunities for Shetland. *STEP Placement*, pp.1–38.

Gorman, D.G. & Neilson, J. (1998) *Decommissioning Offshore Structures*. Springer London.

Hamzah, B. a. (2003) International rules on decommissioning of offshore installations: Some observations. *Marine Policy*, 27 (4), pp.339–348.

IAEA (2000) *Recycle and reuse of materials and components from waste streams of nuclear fuel cycle facilities*.

IMO, (International Maritime Organisation) (2014) International Maritime Organisation [Internet]. Available from: <http://www.imo.org/About/Pages/Default.aspx>.

ISO 14044:2006 (2006) *Environmental Management - Life Cycle Assessment - Requirements and guidelines*.

Jahn, F., Cook, M. & Graham, M. (2008) *Hydrocarbon Exploration & Production*. 2nd ed. Elsevier.

Kaiser, M.J., Pulsipher, A.G. & Byrd, R.C. (2003) Decommissioning Cost Functions in the Gulf of Mexico. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 129 (December), pp.286–296.

Kerr, S. a., Side, J.C. & Gamblin, R. (1998) the Quantification of Energy Consumption and Gaseous Emissions Associated With Decommissioning Offshore Oil and Gas Installations. *Civil Engineering and Environmental Systems*, 15 (4), pp.251–273.

Klöpffer, W. & Frischknecht, R. (2013) *Global life cycle inventory data for the primary aluminium Industry*.

Lakhal, S.Y., Khan, M.I. & Islam, M.R. (2009) An 'Olympic' framework for a green decommissioning of an offshore oil platform. *Ocean and Coastal Management*, 52 (2), pp.113–123.

Lynch, J. (2015) *Rose Field Decommissioning Environmental Impact Assessment*.

MacGregor (2015) *Offshore AHC cranes*.

MacTech Offshore Subsea and Topside Multi-String Casing and Structure Cutting.

Ngu Pei Jia, A. (2013) LCA for Offshore Installations Decommissioning: Environmental Impact Assessment. Universiti Teknologi Petronas.

NOAA (2006) Ocean Explorer: Expedition to the deep slope. , 2007.

Oil & Gas UK (2012) *The Decommissioning of Steel Piled Jackets in the North Sea Region*.

Osmudsen, P. & Tveteras, R. (2003) Decommissioning of petroleum installations - major policy issues. *Energy Policy*, 31 (970911), pp.1579–1588.

OSPAR Commission (2013) 2013 Update of the inventory of oil and gas Offshore Installations in the OSPAR Maritime Area. *Offshore Industry Series*, p.11.

Ovaska, J.-P., Poutiainen, P., Sorasahi, H., Aho, M., Levänen, J. & Annala, M. (2016) *Business Models for a Circular Economy 7 Companies Paving the Way*.

Poremski, H. (1998) *Life Cycle Assessment - Development Planning through Decommissioning*. Berlin.

Pulsipher, A.G. & Daniel IV, W.B. (2000) Onshore disposition of offshore oil and gas platforms: Western politics and international standards. *Ocean & Coastal Management*, 43 (12), pp.973–995.

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.-P., Suh, S., Weidema, B.P. & Pennington, D.W. (2004) Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment International*, 30 (5), pp.701–720.

Reck, B.K. & Graedel, T.E. (2012) Challenges in Metal Recycling. *Science*, 337 (2011), pp.690–695.

Sadeghi, K. (2007) An Overview of Design , Analysis , Construction and Installation of Offshore Petroleum Platforms Suitable for Cyprus Oil / Gas Fields. *Journal of Social & Applied Sciences*, 2 (4), pp.1–16.

Schroeder, D.M. & Love, M.S. (2004) Ecological and political issues surrounding decommissioning of offshore oil facilities in the Southern California Bight. *Ocean and Coastal Management*, 47 (1–2), pp.21–48.

Scottish Enterprise (2002) *Offshore Decommissioning: Opportunities for Scottish Based Businesses*.

Seier, M. & Zimmermann, T. (2014) Environmental impacts of decommissioning nuclear power plants: methodical challenges, case study, and implications. *The International Journal of Life Cycle Assessment*, 19 (12), pp.1919–1932.

Shell Int. Ltd. (2008) *Brent Spar Dossier*. Available from: <http://www-static.shell.com/content/dam/shell/static/gbr/downloads/e-and-p/brent-spar-dossier.pdf>.

Statoil (2011) *Decommissioning and disposal of Statfjord: A Proposed impact assessment programme*.

Stokes, A.W. Deepwater Structure Removal Analysis. *Offshore Network Ltd*, (8702032).

Swartz, K.I. (2015) Setting the standard. *Vertical*, (April). Available from: <http://www.verticalmag.com/news/article/31306#>.

Thornton, W. & Wiseman, J. (2000) Current Trends and Future Technologies for the Decommissioning of Offshore Platforms.

Tremeac, B. & Meunier, F. (2009) Life cycle analysis of 4.5MW and 250W wind turbines. *Renewable and Sustainable Energy Reviews*, 13 (8), pp.2104–2110.

Wallbridge, S., Banford, A. & Azapagic, A. (2013) Life cycle environmental impacts of decommissioning Magnox nuclear power plants in the UK. *The International Journal of Life Cycle Assessment*, 18 (5), pp.990–1008.

Watkins, M. & Passow, S. (2002) *Sunk Costs: The Plan to Dump the Brent Spar*. Cambridge, MA.

Winslow, R., Crawford, G.L. & Broadbent, C. (2012) *Lci data for steel products*.

Zhijun, F. & Nailing, Y. (2007) Putting a circular economy into practice in China. *Sustainability Science*, 2 (1), pp.95–101.

APPENDIX A

Main LCI data for the production of 1 tonne of primary aluminium

Main raw materials (kg)	
Bauxite	4,272
Limestone (calcium carbonate)	261.5
Sodium chloride	112.6
Fossil-based energy resources (kg)	
Crude oil (crude)	762
Hard coal (crude)	892
Brown coal (crude)	756
Natural gas (crude)	650
Main emissions to air (kg)	
Carbon dioxide	8,566
Nitrogen oxides	14.0
Sulphur dioxide	34.2
Methane	14.3
Fluorides (particles)	0.55
Hydrogen fluoride	0.60
Group PAH to air	0.151
Benzo[*a*] pyrene	0.0024
Tetrafluoromethane	0.109
Hexafluoromethane	0.010

APPENDIX B

Main LCI data for the production of 1 tonne of cast steel

	Iron ore sinter plant	Blast furnace	Lime production plant	Basic oxygen furnace	Casting plant	Hot rolling
Inputs						
Iron ores	1202.68	36.76	-	-	-	-
Limestone	180.16	-	123.13	-	-	-
Dolomite	34.25	-	-	5.34	-	-
Iron ore sinter	-	1307.71	-		-	-
Pellets	-	250.00	-		-	-
Pig iron	-	-	-	947.16	-	-
Iron scrap	-	-	-	295.54	-	-
Lubricating oil	3.50	2.19	0.03	-	2.46	33.85
Tap water	-	0.35	-	90.60	0.54	13.27
Electricity	79.20	25.52	2.52	27.80	10.62	40.49
Natural gas	-	0.39	5.53	0.41	0.10	2.71
Emissions						
CO_2	377064	808452	50566	29500		106791
SO_2	1014	10	-	6		4
NO_2	773	18	6	4		21
CO	25849	963	5	4797		19
Pb	6.11	0.05	0.03	0.97		-
Cr	0.04	0.02	-	0.13		-
Cd	0.12	-	0.00	0.05		-
Cu	0.67	0.49	0.03	3.22		0.00
Zn	1.08	0.90	0.08	7.82		0.00
Ni	0.06	0.07	-	0.29		-
Fe	128.45	61.08	0.39	63.29		0.05

Dust	458.55	87.91	16.03	188.97		0.09
HF	0.52	-	-	-	-	-
HCl	4.99	-	-	-	-	-
H_2S	-	0.11	-	-	-	-
HCN	-	0.88	-	-	-	-