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Assessing environmental impact of discharge to sea from producing subsea installation with DREAM following life cycle thinking: a preliminary study for the environmental footprint

by

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MSc Thesis

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Abstract

Assessing environmental impact of discharge to sea from producing subsea installation with DREAM following life cycle thinking: a preliminary study for the environmental footprint

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The purpose of this study was to quantify the environmental footprint of discharge to sea from a producing subsea installation and its semi-submersible host platform in the North Sea. Portion of environmental burden that could be allocated to each installation was identified. Having no physical discharge point, specific portion produced water and waste generated from subsea installations have not previously been studied. Main concepts and methodology of the established life cycle assessment was followed through life cycle thinking using real data for best estimation of the posed risk and impact. Dose-response risk and assessment model was implemented as currently the best available tool for impact assessment of the complex mixture the discharge is composed of. All sources of discharge during the production phase were identified and assessed, and DREAM results evaluated the subsea contribution to risk by the discharge. A more comprehensive evaluation of all phases of the life cycle including more impact factors is needed to properly evaluate the total environmental footprint by a subsea installation.

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List of Abbreviations

AP	Alkylphenol
BAT	Best available technology
BRD	Biomarker response distribution
BTEX	Benzene, toluene, ethylbenzene, and xylene
CO_2	Carbon dioxide
DREAM	Dose-Response Environmental Assessment Model
EEH	Environmental Hub
EIF	Environmental Impact Factor
ERA	Environmental Risk Assessment
EU	European Union
FLAGS	Far North Liquids and Associated Gas System – natural gas pipeline in the North Sea
HOCNF	Harmonised Offshore Chemical Notification Format
HSE	Health, safety and the environment
H_2S	Hydrogen sulfide
ISO	International Organisation for Standardisation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MEG	Monomethyl glycol
NCS	Norwegian Continental Shelf
NORM	Naturally occurring radioactive material
N_2O	Nitrous oxide
OEF	Organisation Environmental Footprint
OSPAR	Oslo-Paris Commission for the protection of the Marine Environment to the North-East Atlantic
PAH	Polycyclic aromatic hydrocarbon
PEC	Predicted Effect Concentration
PNEC	Predicted No Effec Concentration
PEF	Product Environmental Footprint
PL	Production Licence
PLONOR	Pose Little Or No Risk to the marine environment
PW	Produced water
TEG	Triethylene glycol
UK	United Kingdom
VOC	Volatile Organic Compounds
WET	Whole Effluent Toxicity

1. INTRODUCTION

Since the first oil was discovered and production started, the development rate of petroleum fields has increased exponentially around the globe. Today we find petroleum products everywhere we go. Following the awareness of global warming we have seen an increased focus on potential environmental impacts due to petroleum production. Extensive policies and regulations are continuously improved to ensure a more sustainable industry. Discharge of produced water (PW) is the largest waste stream from offshore production emphasising the need for an understanding of potential adverse effects it poses. Discharges are only required to be reported from the physical point of discharge. Subsea installations on the Norwegian Continental Shelf (NCS) (except for Snøhvit) are tied to host platforms and therefore do not have direct emission or discharge sources during normal production. A new term, environmental footprint, is currently raising interest (Gao, 2013). The European Union (EU) defines environmental footprint as "*a comprehensive assessment of environmental impacts over a life cycle*" (The European Commission, 2013). Environmental footprint originates from the method of Life Cycle Assessment (LCA). It is a comprehensive method based on the ISO14040-14044, evaluating the total impact of a studied product or process over its whole life span. Time and resource constraints can set limitations for a full LCA. The Dose-response Risk and Effects Assessment Model (DREAM) calculates an environmental impact factor (EIF) for offshore discharges. Following life cycle thinking, it is possible to combine these methods. This study incorporates the EIF in the inventory analysis for assessment of marine ecotoxicity from discharge to sea. This is the first study focusing on the contribution to environmental impact from a subsea installation. This work is a

contributing part in the development of a model to calculate the total environmental footprint from Vega-production and host semi-submersible platform Gjøa.

1.1. Objective and scope

Wintershall has initiated the assessment of the environmental footprint of Vega towards environmental improvements as it is not clear how large the contribution to the environmental impact is today. The total work load of assessing Vega was split into emissions to air and discharge to sea. The objective for this work is to quantify the environmental footprint of Vega subsea installation and host platform Gjøa, limited to sources contributing to discharge to sea.

The scope of this thesis involves studied production developments during normal production phase, and was set in view of the available data and timeframe. Emission to air is not included. Well interventions are included for the subsea template. Available databases contain historical discharges reported from both the subsea template and the host platform. Discharges caused during exploration, development, and potential accidents are outside the scope of this thesis. Figures of overviews of total systems were made in corporation with another master student Guro Oktavia Fløysvik (University of Stavanger), writing about emissions to air from the same installation.

1.2. Deliverables

To achieve the objective for this master's thesis, the following deliverables were defined by Wintershall:

- Define boundaries for environmental footprint extension (i.e. phases/activities to include),
- Data collection of environmental data for Vega and Gjøa,
- Establish calculating model for host emissions, and
- Presentation of total environmental footprint in end report.

2. THEORETICAL BACKGROUND

Oil and gas production on the NCS started in the 1970s. Assessments of potential environmental harm posed by the industry was however not prioritised until the early 1990's. Up until this time, discharge oil based drilling mud was unregulated resulting in drill cuttings being the largest contributor of oil in the sea (Bakke et al., 2013; Research Council of Norway, 2012). Currently, the main sources of discharged oil to the North Sea and the Norwegian Sea are PW and shipping (The Norwegian Envrionment Agency, 2016).

All operators on the NCS are required to report emissions and discharge from offshore platforms, however from the physical discharge point. Subsea installations are connected to host platforms, hence the discharge is only reported from the host. Chemicals discharged during drilling and well interventions are exceptions as these require separate drilling rigs or vessels. On paper, subsea installations are subsequently classified as green and it is often not clear for the operator of a tie-in how large the impact caused only by these installations. With all companies wanting to reduce their environmental impact, awareness of what is released into the environment is essential. With that known it is further possible to decide where, and what measures can be taken to reduce the impact.

2.1. Produced water

PW originates from the reservoir and is water produced alongside extracted hydrocarbons. It is a complex mixture typically containing dispersed oil, monocyclic and polycyclic aromatic hydrocarbons (PAH), alkylphenols (AP), heavy metals, naturally occurring radioactive material (NORM), organic substances, organic acids, inorganic

salts, mineral particles, sulphurs and sulphides (Research Council of Norway, 2012). Composition and characteristics as highly dependent on the reservoir specific geochemistry, the chemistry of hydrocarbons, and the chemicals added for a safer production and an enhanced recovery (Bakke et al., 2013). Volumes of generated PW is expected to increase with the age of the producing field, oil fields also having higher expected volumes than gas fields (Zheng et al., 2016). Yearly discharge of PW on the NCS varies between 130 and 150 million Sm^3, where 138 million Sm^3 was discharged in 2016 (Norsk olje & gass, 2017). Given the volumes discharged, PW is the largest waste stream from the offshore petroleum producing facilities (dos Santos et al., 2014; Durell et al., 2006; Røe Utvik, 1999; Veil et al., 2004). Contaminants are often discharged in low concentrations lowering potential impacts. A concern is that there is no limit for allowed volumes of discharged PW to the water column and it is a waste product that is generated during the whole life span of a field and continuously discharged (Lee et al., 2005; Neff et al., 2011). While drilling mud and cuttings are only discharged during drilling operations for comparison.

PW is separated from the well stream and treated to reduce content of hydrocarbons to allowable limits before being discharged to the sea. Total allowed concentration of oil in PW is 30 mg/l as monthly middle (Miljødirektoratet, 2016). Even after treatment, the water may still contain residual traces of hydrocarbons and chemicals. Separation technology such as hydrocyclones effectively remove most of dispersed (insoluble) oil droplets, however dissolved hydrocarbons remain in the water phase and are discharged with the PW stream (Pampanin & Sydnes, 2013; Zheng et al., 2016). As of today, discharges from oil and gas production have not been proven to cause harmful effects to

species or populations (The Norwegian Envrionment Agency, 2016). It does not imply that no future long-term effects will be encountered.

2.2. Fate and distribution of contaminants

Hydrocarbons and chemicals discharged to sea have the potential to cause acute and/or chronic toxic effects to organisms in the recipient. Some of the potential effects on organisms include changes in metabolic, biochemicals and molecular responses, behavioural changes, reproduction, lethality, and/or inhibited growth (Smit et al., 2009). Constituent components in PW are in the sea subjected to several processes including evaporation, dissolution, emulsification, oxidation, sedimentation, biodegradation, dispersion, and absorption on suspended solids (Lee et al., 2005). Once discharged, toxic concentrations of contaminants are diluted very quickly only leaving traces limited to < 2 km (Bakke et al., 2013).

2.2.1. NATURAL COMPONENTS

PAHs, APs (octyl- and nonyl-phenols) and heavy metals are especially of environmental concern (Neff et al., 2011). High levels of phenols and low-molecular-weight aromatics are commonly found in gas condensate producing fields (Zheng et al., 2016). Of all components in PW, PAHs are considered the most important contributor to ecological hazard (Neff et al., 2006). PAHs present in PW can be both in the dispersed and dissolved form (Pampanin & Sydnes, 2013), depending on their weight.

Monocyclic aromatic hydrocarbons, namely benzene, toluene, ethylbenzene and xylene (BTEX) compose the largest fraction of dissolved hydrocarbons in PW (Johnsen et al.,

2004; Røe Utvik, 1999). Gas fields contain a higher fraction of low molecular weight BTEX compounds than oil fields and are therefore more toxic (Johnsen et al., 2004; Veil et al., 2004). Being highly volatile, BTEX compounds evaporate rapidly from seawater (Bakke et al., 2013; Chowdhury et al., 2009). They pose a low risk compared to heavier aromatic hydrocarbons and are therefore often ignored in impact studies (Chowdhury et al., 2009; Neff et al., 2006).

2.2.2. CHEMICAL ADDITIVES

Chemicals are added to the system for enhanced recovery of hydrocarbons, protection of equipment, as an aid in separation processes, or to prevent formation of gas hydrates (Neff et al., 2011). Environmental threat posed by chemical additives are highly dependent on the components and the cleaning process before discharge. About one third of the chemicals used for offshore is discharged with PW on the NCS (The Norwegian Envrionment Agency, 2016). Aging fields typically increase the need for chemicals for an efficient extraction of hydrocarbons.

Even with low discharge concentrations considered to have no effect on the environment, organisms in direct contact with a discharge point over a longer period might potentially be biologically affected. Corrosion inhibitors and biocides tend to have the largest contribution to risk (Miljødirektoratet, 2016). Highly variating PW chemistry from different producing platforms require field-specific modelling of fate and effects that the discharged PW poses to marine species (Røe Utvik, 1999).

2.3. Regulations and legislation

Norway is one of the world leading countries when it comes to environmental focus on solutions and technology. And it is argued that Norway has the most developed regulations for the offshore petroleum industry in the world (Zheng et al., 2016). What motivates oil and gas companies in Norway to work as environmentally as possible is mainly the pressure from extensive regulations and legislation issued by the government. Another driving force is fines in the case of higher emissions or discharge than quotas or approvals allow. Having a transparent system where all companies publish updated numbers each year, large deviations quickly make the headlines resulting in undesirable bad reputation and investigation. Most of regulations and legislation given in Europe are implemented to Norwegian laws shortly after. The Norwegian Petroleum Directorate (NPD) has issued several documents regulating the offshore petroleum industry. Main regulations motivating reduction of discharge to sea is included below.

2.3.1. THE FRAMEWORK HSE AND ACTIVITIES REGULATION

The Framework HSE regulation aim to protect health, safety and the environment related to petroleum activities. Operators on the NCS are required to perform environmental monitoring to assess, and map possible pollution caused by the petroleum activities present, cf. §48 and §34 (The Framework HSE Regulation, 2017).

The Activities regulation describes more in detail exactly how monitoring activities should be carried out. It is referred to the "Guidelines for environmental monitoring of the petroleum activities offshore" for further explanation of requirements (Norwegian Environment Agency, 2015). Sediments, benthic fauna and the water column should all

be monitored regularly, cf. §52-56 (The Activities Regulations, 2017). Annual reports of total emissions and discharge are required from all operators.

2.3.3. ZERO DISCHARGE TARGET

The zero-discharge target is an important drive towards reduction in the environmental impact. The target was established in a cooperation between companies in the industry and the Norwegian government in 1997 and refers to a goal of no discharge of hazardous substances to sea on the NCS (Norwegian petroleum, 2017). All planned discharges need approval from the Norwegian Environment Agency. Operators on the NCS must be able to demonstrate that they are not exceeding allowable limits and are constantly taking measurements for reporting. Given the zero-discharge target, the government want all discharge to be as low as possible, regardless of hazardous potential.

2.3.4. OSPAR AND HOCNF

The Oslo-Paris (OSPAR) Commission works with identification and elimination of treats, for protection of the Marine Environment of the North-East Atlantic. OSPAR has established a protocol on methods for testing offshore chemicals including the OSPAR Guidelines for Toxicity Testing of Substances and Preparations Used and Discharged Offshore (OSPAR Commission, 2005).

Toxicity testing on selected marine species is required for all chemicals before becoming available on the NCS market. Suppliers must provide information and data of all offshore chemicals to the operator according to The Harmonized Offshore Chemical Notification Format (HOCNF). This format lists the impact of chemicals on the marine environment according to standardised forms by OSPAR (OSPAR Commission, 2015). A fish larva

(*Scophthalmus maximus*), a crustacean (*Acartia tonsa*), and an alga (*Skeletonema costatum*) has been selected as representative species for the whole water column (Norsk olje & gass, 2003). Substances considered "sinkers", adsorb easily to particles rather than move through the soil (Koc > 1000), have high potential to bioaccumulate (Pow > 4), or contain surfactants, also have to be tested on a sediment reworker (*Corophium valuator*). A discharge permit approved by the authorities is based on the properties of the chemicals listed in the HOCNF.

Based on results on toxicity testing in the HOCNF, chemicals are categorised in a colour code classification system ranging from green, yellow, red to black. Test result requirements for each colour code is given in §63 of The Activities regulation and listed in Appendix 1. Black chemicals are posing the largest threat having low biodegradation and high bioaccumulation potential. Green chemicals are also known as substances on the PLONOR list, considered to pose little or no risk to the environment when discharged to sea, provided by OSPAR (OSPAR Commission, 2018). Green chemicals can be used and discharged offshore.

2.4. Life Cycle Assessment

LCA is a comprehensive method for calculating the environmental footprint of a product or a process over its entire life cycle from extraction of raw material, to production and use, to waste management. It aims to be a tool for policy or decision makers reaching environmental solutions. A LCA can be conducted either on a single product system, also called a stand-alone LCA, or as a comparison study between several products.

Techniques like LCA were first developed in Europe and the USA in the early 1970s for comparison of different packaging of products (Andresen & Li, 2011; Azapagic, 1996). Scientists then begun to realise that industries were causing environmental issues (Boustead, 1996; Hunt et al., 1996). Expanding the field of application over the next decades, a standardised technique was needed. In 1997, the International Organisation for Standardisation (ISO) issued the standard ISO 14040 regarding principles and framework in LCA (Rebitzer et al., 2004). ISO standards for LCA were last updated in 2006 when the new standards 14040 and 14044 were published. Various methods and guidelines are described in the literature. They have in common that they follow a main framework and stages of the method presented in Figure 1 and described below.

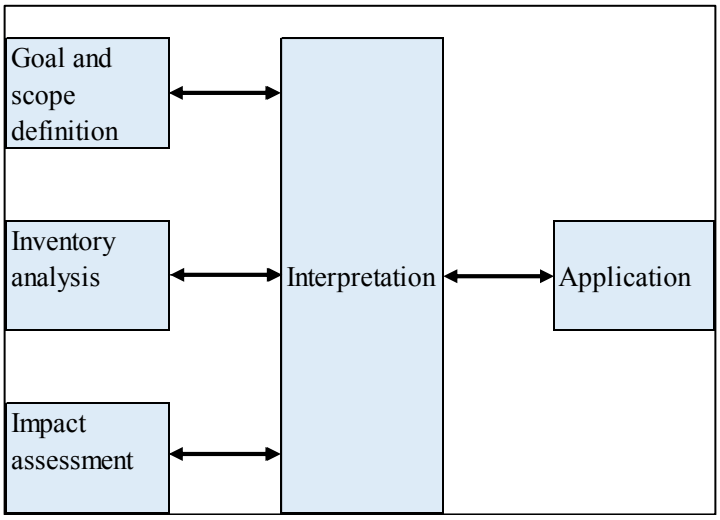


Figure 1 - Framework and relationship between stages of a LCA. Modified from ISO 14040 (2006).

Goal and scope definition

Goal and scope definition involves defining the motivation of studying the product of process, aim of the work, intended application, and audience or users of the results

(Guinée et al., 2002). The scope defines clear boundaries for which process factors to include in terms of extent of geographical area, timeframe, and limits of the technical system. Finally, the product or process of the study is described with the applied functional unit, and reference flows (Guinée et al., 2002). Clear boundaries of the study provide better transparency and validity of the study and final results.

Inventory analysis

The inventory analysis is performed within the set boundaries of the goal and is a difficult and tedious process (Andresen & Li, 2011). It is also called an input/output analysis as it aims to document all data that can enters and leave the studied process with a mass balance. Data collection is described as the most time consuming process by several authors (Mitchell & Hyde, 1999). Inputs include raw material, energy, and physical products, while outputs include wastes, products, and other emissions (Andresen & Li, 2011; Jacquemin et al., 2012). The inventory analysis is often based on either a mass balance or energy balance and presented as a flow chart to give a clear presentation.

Impact assessment

The impact assessment is a challenging step without no clear requirements of the methodology. For the assessment, suitable impact factors are assigned to the output from the inventory analysis to relate environmental stressors to environmental consequences and thereby characterise the impact. The impact assessment can be divided into two steps: classification and characterisation. Each component quantified in the inventory analysis is classified into impact categories or factors, depending on what department of the environment they have potential to affect. Assigned categories can be at midpoint (global warming potential, acidification, eutrophication, land use, water use, toxicology,

and more) or endpoint (damage to ecosystem, human health. etc.) level. Included impact factors depend on the goal and scope description of the study.

Substances within one impact category are translated by characterisation factors to a common unit or equivalent. One example is greenhouse gases being translated into CO_2-equivalents for global warming potential (Miseljic & Olsen, 2014). The translation from the inventory to the impact assessment has been described as the most difficult phase of the whole assessment (Jacquemin et al., 2012). A weakness to the full LCA often lies with the quality of data (Von Bahr & Steen, 2004). Several software tools have been developed easier application including Eco-indicator 99, GaBi, SimaPro, CML 2001 with available databases (Jacquemin et al., 2012; Pieragostini et al., 2012). Collecting data through these software tools avoid the issue of lack of data. However, these data are general meaning and they do not originate from the actual studied process or product.

Interpretation and application

Interpretation is where conclusions of the environmental damage is taken based on the results from the impact assessment step. Final results are seen in the light of the scope. Recommendations for reduction of environmental impacts is described. Application can be directed towards policy making, decision making for product improvement or development, and more.

The technique is applicable for a large variety of products and several studies have now applied LCAs: to the process industry (Jacquemin et al., 2012), to alternative hydrocarbon fuel conversion (Andresen & Li, 2011), and for electricity generation (Stamford & Azapagic, 2014). Few publishments focus on offshore produced water

management (Veltman et al., 2011; Zheng et al., 2016). No studies were found during the literature review to have investigated the discharge from a seabed producing template. In existing literature, authors agree that there are large inconsistencies between applications (Jacquemin et al., 2012; Wiedmann & Minx, 2008); (Mitchell & Hyde, 1999). Clarification of system boundaries, how data for the inventory was collected, and impact assessment approach are criteria needed to avoid weakness and increase transparency of a LCA study. Results further have to be viewed in in terms of mentioned criteria (Andresen & Li, 2011), and limitations should be explained (ISO 14040, 2006).

Performing a LCA including all steps in a product system's life cycle is referred to as a cradle-to-grave approach (Jacquemin et al., 2012). It is always desirable to include every step in a product's life cycle. Lack of data or knowledge regarding use and disposal may prevent the possibility to follow a product or a process from cradle to grave. Modified approaches are cradle-to-gate and cradle-to-cradle referring to a product life until use and recyclable products respectively (Landis, 2010).

2.5. Dose-related Risk and Exposure Assessment Model

DREAM is an established risk assessment model for simulation of fate and distribution of complex water mixtures, including natural components and a variety of added chemicals released to sea. It is a numerical model calculating the risk PW pose to recipient biota when discharged to sea. The software was developed by the SINTEF research centre in a joint effort with major operator companies in the industry, after Norway decided to work towards zero harmful discharges. As a member of OSPAR, Norway is committed to implement environmental risk assessment (ERA) of PW after OSPAR recommendation

2012/5 and this is fulfilled with the calculation of EIF (Miljødirektoratet, 2016). The aim for DREAM results is to be a tool for decision makers identifying environmental solutions. All operators discharging PW on the NCS are today required to include results of a DREAM model in the impact assessment before starting production. Operators strive to document that their production discharge yield an EIF < 10 as a new simulation is required every year it exceeds this threshold value.

Each added chemical is described by one, or several, components with a set of physical, toxicological and chemical parameters. Natural components are compiled in groups having a selected component representing a Predicted No Effect Concentration (PNEC) value as the input components. The applied DREAM model concept is a Lagrangian approach where particles represent the concentration field of each component (Reed & Hetland, 2002). The particles can be dissolved substances, solids, and droplets of e.g. oil. From the discharge point, travel path of these particles is estimated based on comprehensive input values. Geographical area specific input values include sea currents, geographical location, winds, salinity, depth of discharge, and field specific data on components of the PW. Resulting outputs from the simulation are given in a risk map, a hazard identification map and a quantified value of the EIF based on a PEC/PNEC approach, where PEC is the Predicted Effect Concentration.

PNEC is the highest concentration considered to have no measurable harm on the environment or surrounding species. Separate PNEC values are given for each component in the calculated discharge water. The values are derived from laboratory toxicity testing by LC50 (concentration for lethality of 50 % of tested species), EC50 (concentration for predicted effect of 50 % of tested species) or NOEC (No Observed

Effect Concentration) (Rye et al., 2004). PNECs for natural occurring components in PW are reported in the EIF computational guidelines provided by the Norwegian Oil and Gas Association (NOROG) (Norsk olje & gass, 2003). HOCNF scheme reports contain information needed to find PNEC values for added chemicals.

PEC is calculated by the DREAM model and is based on the fate of chemicals included in the model. It is three-dimensional and time variable solved in a generalised equation in the model (Reed & Hetland, 2002):

$$\frac{\partial C_i}{\partial t} + \vec{V} \cdot \vec{\nabla} C_i = \vec{\nabla} \cdot D_k \vec{\nabla} C_i + \sum_{j=1}^{n} r_j C_i + \sum_{j=1}^{n} \sum_{i=1}^{n} r_{ij} C_i \quad (1)$$

Where:
C_i = concentration of the i^{th} chemical constituent in the release,
t = time,
$\vec{V}$ = advective transport vector,
$\vec{\nabla}$ = gradient operator, and
D_k = turbulent dispersion coefficient in k = x, y, z directions.

And the terms r_j are process rates, including:

- Addition of mass from continuous release,
- Evaporation from surface slicks,
- Spreading of surface slicks,
- Emulsification of surface slicks,
- Deposition from water surface onto coastline (breaching),
- Entrainment and dissolution into the water column,
- Resurfacing or entrained oil,
- Volitalisation from water column,
- Dissolution from sediments to water column,
- Deposition from water column to bottom sediments,
- Removal from coastline to water column/water surface, and
- Mass removal cleanup.

Process specific equations have been developed for every process such as currents and winds. These are described by Reed and Hetland (2002). DREAM is the most comprehensive of models developed in terms of including processes the contaminants are subject to (Neff et al., 2011). Field work determining measured environmental concentration is an alternative to calculating the PEC (Lam & Gray, 2001). However, the high dilution rates once chemicals in a discharge are introduced to the sea makes it difficult to measure the discharge concentrations *in situ* (Sanni et al., 2017).

2.5.1. ENVIRONMENTAL IMPACT FACTOR

EIF is an indicator of environmental risk caused by a simulated discharge. It was developed to give one value to a total discharge of complex mixtures, and for comparison of discharges from different fields. With the PEC/PNEC based calculation approach, the PEC of every component in the PW is compared to the corresponding threshold limit value, PNEC for the same component. The approach originates from species sensitivity distribution (SSD), a probability model for evaluation of variation in distribution of species based on acute and chronic endpoints exposed to different contaminants (Aldenberg et al., 2002). SSD curves are plotted with concentration of toxin (often based on NOEC and given in log) against sensitivity of species by the potentially affected fraction (PAF) of species in a sigmodal shape (Sanni et al., 2017). PNEC values can be extrapolated from SSD curves being the 5^{th} percentile of NOEC or PAF (Sanni et al., 2017; Smit et al., 2009). When PEC exceeds PNEC it indicates a possible occurrence of potential adverse effects larger than 5 %. With a PEC lower than the PNEC, the risk is assumed to be acceptable. The calculated value of EIF is defined as the volume where PEC/PNEC is larger than 1 in a volume of recipient water of 100 m x100 m x10 m (= 100 000 m^3). This value corresponds to a probability to impact 5 % of the most sensitive

species (Figure 2). EIF contribution from each component of a discharge is presented in a pie chart in the final report. The total EIF value is conservative meaning it corresponds to input of worst case scenario values for every compound.

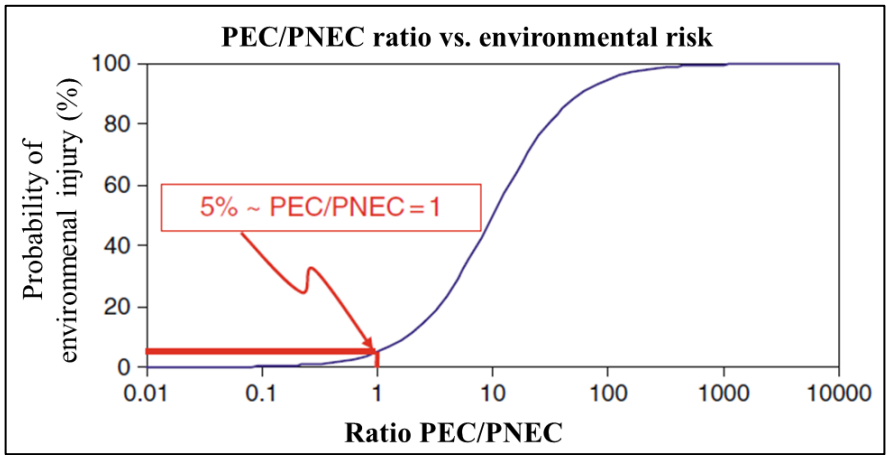


Figure 2 – PEC/PNEC ratio versus environmental risk. Modified from (Reed & Rye, 2011). PEC = Predicted Effect Concentration, PNEC = Predicted No Effect Concentration.

EIF results are available from all fields on the NCS. It is not only a good tool for evaluating whether a solution is environmental or not, but also for different operators to compare their discharges. Comparing different technology solutions looking at their respective EIF value has been a favoured decision maker tool for field developers finding the best available technique (BAT). Contribution to the total EIF (in %) from each component in the discharge makes it possible to locate which chemicals pose the largest threat to environmental risk. Results are used as argumentation in impact assessments for approval and selection of cleaning technology.

Calculation of the EIF is considered the best available tool for comparison of discharge from different installations to the same recipient (Miljødirektoratet, 2016). In addition, it

gives a good overview of which chemicals or natural components have the largest contribution to increased risk level. With a calculated EIF it is possible for the operator to evaluate which components to find environmental solutions for replacement.

2.5.2. BIOMARKER BRIDGE AND WHOLE EFFLUENT TOXICITY

Biomarkers are early signal responses in organisms that can be detected and thereby indicate expected effect or exposure to discharge mixtures rather than just the predicted risk (Sanni et al., 2017). The DREAM model, calculating the risk, can be combined with biomarker results from monitoring for a better understanding of the actual effect of the discharge on the environment. A biomarker bridge is a biomarker response distribution (BRD) plotted against a risk curve. The combined plot can then further be combined with DREAM and be used as a tool to predict in percentages the amount of species that will show biomarker response by the simulated discharge.

While DREAM predicts chemical specific fate and distributions for calculation of risk, a new approach for Whole Effluent Toxicity (WET) has an increased focus on the effect of discharge of chemical mixtures. WET tests are conducted for all chemicals in the solution of a discharge, e.g. oil based discharges (Sanni et al., 2017). Some originally hazardous chemicals at injection to process may react with other chemicals to be non-toxic in the discharge stream (Society of Environmental Toxicology and Chemistry, 2004). OSPAR aims to implement WET modelling in their recommendations. As of today, no field measurements are compared to risk assessments on the NCS other than for research (Sanni et al., 2017).

2.6. Life cycle based assessment approaches

Lack of data, or a narrowed scope may not qualify a study as a complete LCA even if the methodology is followed. A new trend of modified LCAs is emerging (Finkbeiner, 2016). Two main development directions are described, communication-driven for simplified LCAs and sustainability-driven for a sophisticated assessment of eco-efficiency. It is in the simplified direction that we see an increasing number of stand-alone footprints, e.g. carbon footprints related to emissions to air. A LCA study only focusing on one environmental impact can also be called a single-issue method. Finkbeiner (2016) have arranged the new types of LCA in an adaption of Maslow's pyramid (originally developed as a hierarchy of basic human needs) ranging from life cycle thinking to Life Cycle Sustainability Assessment (LCSA) (Figure 3). It is implied that the pyramid does not represent a ranking of what tools are better, but at levels helping to find the best development pathway.

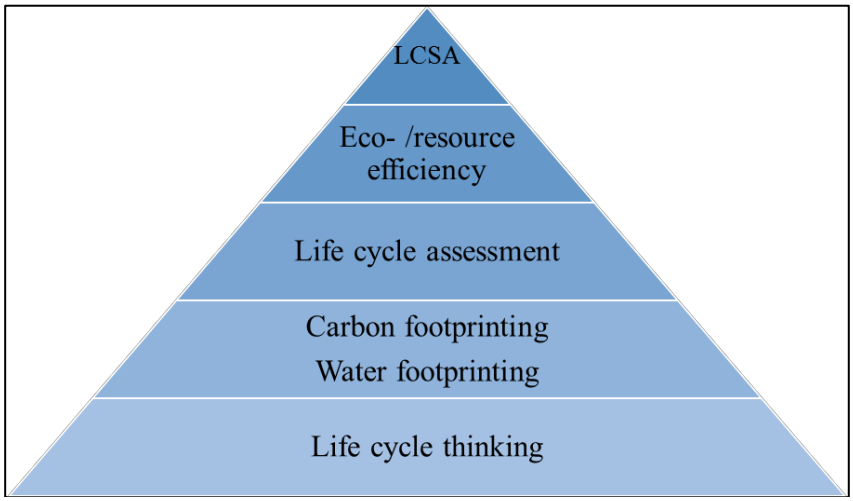


Figure 3 - Adaptation of Maslow's pyramid of human needs for life cycle based environmental and sustainability assessment approaches. Modified from Finkbeiner (2016). LCSA = Life Cycle Sustainability Assessment.

Rebitzer et al. (2004) describe simplified LCAs as a tool for applications where time or resources are not sufficient for a full LCA methodology. Still including the whole life cycle of the studied product, life cycle thinking has been introduced as a basic approach to LCA (Finkbeiner, 2016); (Miseljic & Olsen, 2014). This opens for wider application field, e.g. assessment of only one impact category. Assessments assigned to lower stages of the pyramid can be good complementary assets to complete a full classical LCA and further perform an eco-efficiency study.

2.7. Quantification of the environmental footprint from discharge to sea

A quick search for environmental footprint does not give a clear definition. It is a relatively new term with increasing interest. What is certain is that the term originates from LCA. Several scientists have included the term in their reports, leaving a definition out. The Cambridge dictionary defines environmental footprint as "*the effect that a person, company, activity, etc. has on the environment, for example the amount of natural resources that they use or and the amount of harmful gases that they produce…*"(Cambridge dictionary, 2018). The timeframe is not included in here like the European union (EU) defines it as over the life cycle.

Several studies have branched or adapted the term to carbon footprint including all emissions to air contributing to global warming potential. Not even regarding carbon footprint have scientists agreed on a common definition or method. Some include only gases that contain the carbon element while others include all greenhouse gases such as N_2O (Wiedmann & Minx, 2008). A common impact factor has been found for all components an emission to air to be translated to, namely CO_2 equivalents. PW on the

other hand is more complex mixtures of natural components and chemical additives. Large variations in physical-chemical properties make it challenging to translate all to one common impact factor.

It is impossible to find an absolute measure of environmental impact without field and laboratory studies of exposed species. Performing a LCA implementing DREAM can still be a good indicator of the potential footprint that is left behind. Quantifying the environmental footprint from discharge to sea is for this study interpreted as identifying the amount (in kg) of residual components in the water column over the life cycle (scope includes production phase) of a subsea installation.

3. STUDY AREA

The study area includes Vega and Gjøa fields. These are situated Northern part of the North Sea, North of the Troll field and West of Florø in Norway. Production from both fields started in 2010. These fields were planned together as it was not estimated cost effective to produce from Gjøa alone. PW from Vega and Gjøa has a common discharge point 6 m below sea level. As Vega does not have a direct discharge point it is considered a green installation generating discharge only in the event of well interventions.

3.1. The Vega Field

Vega is a gas condensate field situated on the blocks 35/8 and 35/11 covered by production licences PL 248, PL 448B and PL 090C approximately 370 m below sea level (Norwegian Petroleum, 2018b). The Vega field includes three seabed templates connected to the deposits, Vega North, Vega Central and Vega South (previously Camilla, Belinda and Fram B) (Figure 4). The templates are chained on a 12" multiphase pipeline with an approximate distance of 10-11 km between each template.

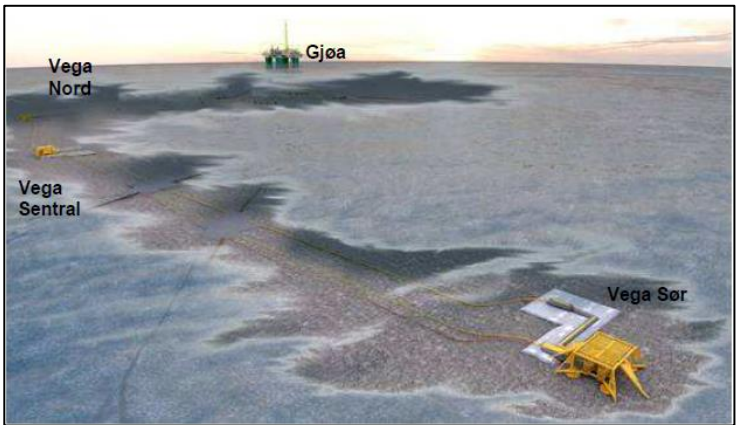


Figure 4 - Overveiw of the Vega Field including three subsea templates. Translation: Nord = North, Sentral = Central, Sør = South. Retrieved from Wintershall (2017).

Each template has two wells drilled and a capacity to double the amount. Currently there is no production from Vega Central due to production constraints at Gjøa. Vega South contains a layer of oil additional to the gas and condensate that Vega North and Vega Central also have. The field is produced with pressure depletion (Norwegian Petroleum Directorate, 2018b). The reservoir rock is Middle Jurassic sandstone with low permeability in the Brent group. Wintershall Norge AS has been operating the field since March 2015 (Wintershall Norge, 2018). The well stream is transported to the host platform Gjøa for processing and transportation. Current share of licences of Vega is presented in Table 1.

Table 1 - Current share of licenses of Vega. Data retrieved from Wintershall Norge (2018).

Company Name	**Licence share (%)**
Wintershall Norge AS	55.6
Petoro AS	28.6
Spirit Energy Norge AS	7.3
Neptune Energy Norge AS	4.4
Idemitsu Petroleum Norge AS	4.4

3.2. The Gjøa Field

Gjøa is an oil and gas producing field on the blocks 35/9 and 36/7, covered by the production license 153 approximately 360 m below sea level (Norwegian petroleum Directorate, 2018a). The Gjøa field consists of a semi-submersible with five templates, named A, B, C, D, and E, connected (Figure 5) (Engie, 2017).

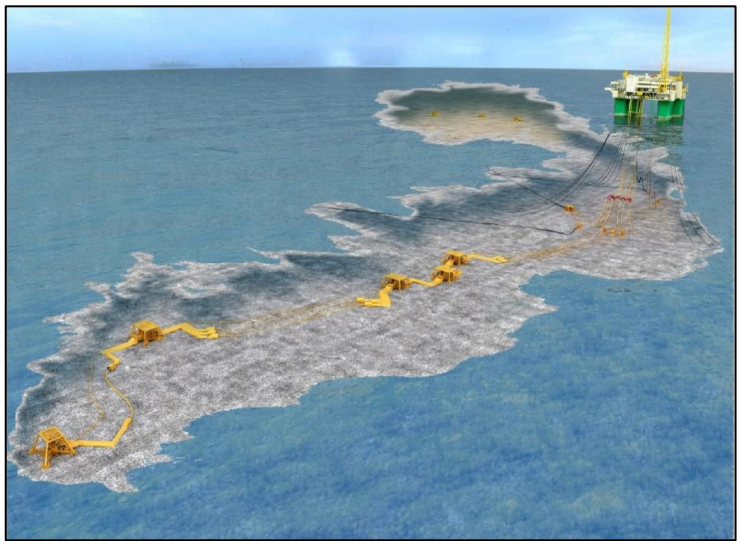


Figure 5 - Overview of the Gjøa field, semi-submersible with subsea installations connected. Retrieved from Engie (2017).

The gas sits over a thin oil zone, about 10-15 m thick. Reservoir rock is Jurassic sandstone in the Dunlin, Brent, and Viking group. Production is by pressure depletion. Production of oil zone prioritized in the first years produced with support from pressure depletion from the gas zone. Production of the gas cap was initiated in 2015, and low-pressure production started in 2017 (Norwegian Petroleum, 2018a). Gjøa is the first semi-submersible platform to be supplied with power from shore through a 100km submersed cable from Mongstad reducing CO_2 emissions. Current share for licenses of Gjøa is presented in Table 2.

Table 2 - Current share of licenses of Gjøa. Data retrieved from Wintershall Norge (2018).

Company name	License share (%)
Neptune Energy Norge AS	30.0
Wintershall Norge AS	20.0
A/S Norske Shell	12.0
Dea Norge AS	8.0
Petoro AS	30.0

3.3. Production process description

An abridged description of Vega and Gjøa production process and systems involved is based on information in internal system books (for processes 20, 21, 24, 27, 38, 42, 44, and 46) provided by Neptune Energy Norge AS (2014). Detailed descriptions are not necessary for understanding where in the process different sources of discharges originate. The production process of Vega has highest focus. An overview of parts of the process included in this study is presented in Figure 6.

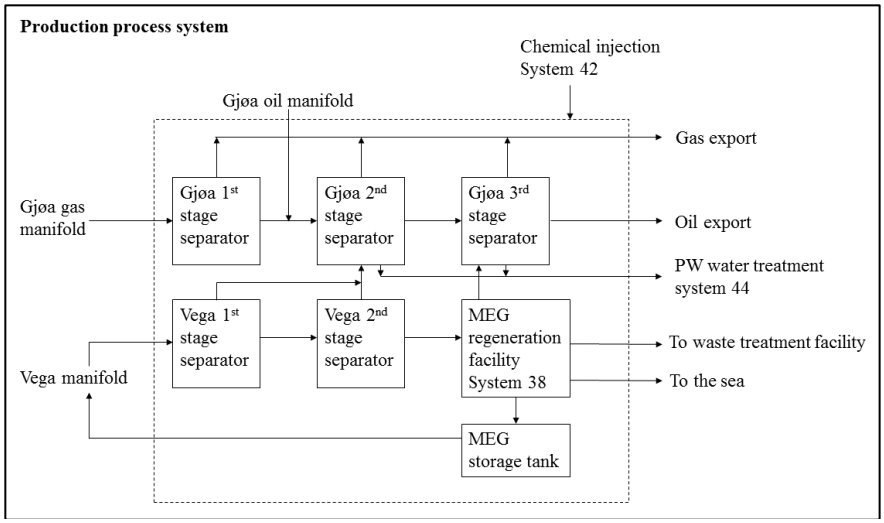


Figure 6 - Simplified overview of Vega and Gjøa production process. Modified from internal documents from Neptune Energy Norge AS (2014).

The Vega wellstream is transported to Gjøa semi-submersible through a 32-km and 14" production line. A lazy-S flexible riser connects the subsea-system to the platform. All processing equipment is installed topside on Gjøa. Produced wellstream is initially led to Vega 1st stage separator, where gas is separated from liquids under a pressure of 35 bar. Monomethyl glycol (MEG) and other chemical additives mixed with water, salts, residue of hydrocarbons as well as sand and other particles is referred to as wet MEG. Condensate and wet MEG is transported to Vega 2nd stage separator, where lower pressure of 20 bar separates additional gas from the liquids. Separation of condensate and wet MEG is assisted by differential pressure. Wet MEG is led to the MEG regeneration system, while the condensate is led to the Gjøa process system.

Produced hydrocarbons from Gjøa are led through a separation process of 3 stages. Gas and condensate from Vega 1st and 2nd stage separators are mixed with the Gjøa processing stream in Gjøa 2nd and 3rd stage separators. Vega gas is led through two compressors and mixed with Gjøa gas before being transported in the export pipeline holding a pressure at about 150 bar. One of the compressors is driven by a gas turbine provided with gas from the production. Vega condensate follows the same processing as Gjøa oil. PW from the Gjøa wellstream is separated out in the 2nd and 3rd stage separators. It is further cleaned topside the platform in system 44, produced water treatment, before discharge.

The chemical injection system, system 42, stores production chemicals in separate storage tanks and injects chemicals at correct dosages by injection pumps. Several systems are connected to the chemicals injection system (Figure 7). Vega production

chemicals are sent from Gjøa topside and injected through the pipeline to the wellheads on each template.

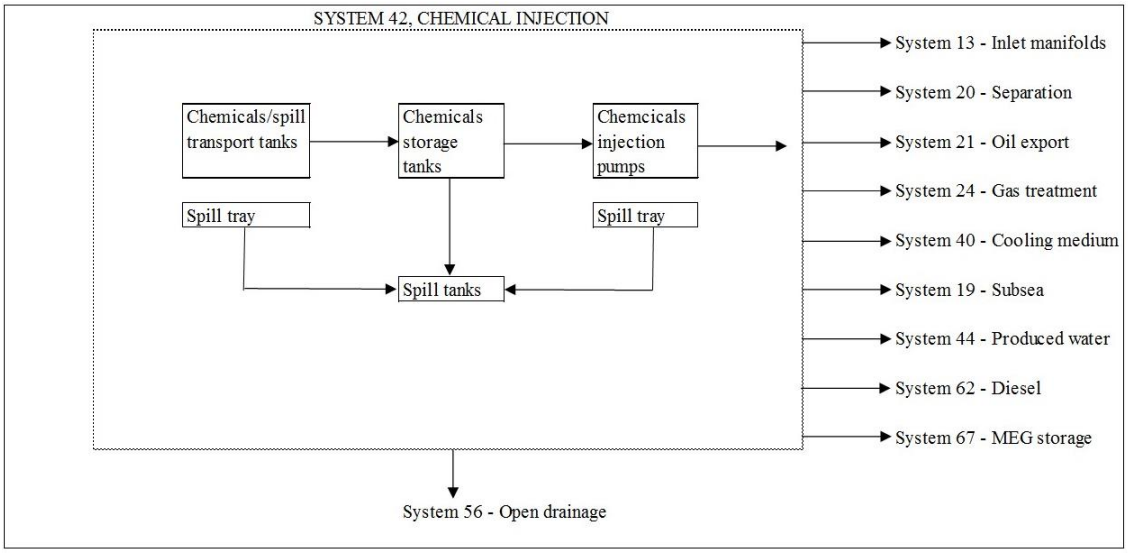


Figure 7 - System 42, Chemical injection. Block diagram including input and output relevant for this study. Simplified from system description 42 provided by Neptune Energy Norge AS (2014).

Wet MEG is led from Vega 2nd stage separator to the MEG regenerating system, system 38. Figure 8 shows an overview of relevant steps of the regeneration process. The purpose of this process is to be able to reuse most of the MEG and hence reduce both discharge and waste. The first step is the degasser holding a pressure of 0,5 bar. Hydrocarbons still absorbed are separated from the wet MEG and led to Gjøa 3rd stage separator. Degassed wet MEG is led to the tank for wet MEG. Excess heat transferred from the gas turbine boils the water off the MEG over the steps of heat exchange, MEG recirculation and distillation. This circuit is continued until desired concentration of 90 % MEG is achieved. The distillation temperature is operated by a vacuum system holding the pressure at -0,5 bar. Temperature is then kept between 110°C and 130°C. Condensed

water is filtered before discharge. Natural salts from the formation and chemical additives are centrifuged to separate additional MEG. Regenerated MEG is stored in a designated storage tank. Salt and chemicals stored in a salt storage tank before transportation by a vessel to an onshore waste treatment plant. The condensed water is filtered before discharged 6 m below the sea level. Most of the discharge of chemicals from Vega production is related to cleaning of the MEG regeneration facility. Up until the end of 2015, the washing water was returned onshore for waste treatment. After changes in procedure, the 1st round is transported onshore while 2nd and 3rd round is discharged to sea.

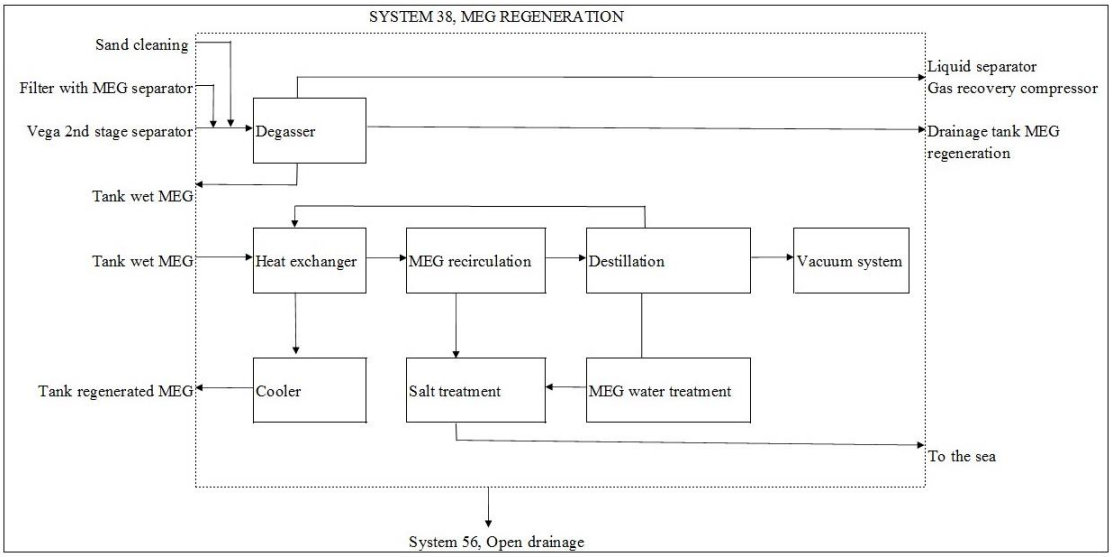


Figure 8 - System 38, Monomethyl glycol (MEG) regeneration. Block diagram including input and output relevant for this study. Simplified from system description 38 provided by Neptune Energy Norge AS (2014).

Stable oil is transported in a 17" pipeline to Mongstad refinery via Troll Oil Pipeline II (Norwegian Petroleum Directorate, 2018b). Rich gas is transported to the St. Fergus terminal in the United Kingdom (UK) in a 30" pipeline through the Far North Liquids

and Associated Gas System (FLAGS). The total distance is 130-km where the last 8.5-km are on British Sector (Statoil, 2006).

3.4. Identified discharge sources

The main source of discharge to the sea originating from Vega is PW. PW from Vega is measured at sampling point 38AP4375 on the outlet pipe from the saline tank to sea. PW from Gjøa has a separate sampling point. Samples of PW are taken from every production installation for analysis at least two times per day. Sometimes four are taken every 24 hours and mixed before analysis. Based on concentrations found in the analysis, updated concentrations of every component are calculated based on volumes measures per day. PW from Vega contain dispersed oil, dissolved organic compounds, and chemicals added during production (Norsk Hydro, 2006) APs, PAHs, BTEX, and organic acids compose the organics of the soluble compounds. NORMs, Zink, copper, led, and nickel are inorganic soluble, while the non-soluble is dispersed oil. Typically, PW is also mixed with injection water increasing performance of production. Vega is produced by pressure depletion; hence no water is injected. Vega is still in the early phase of production and the amount of PW is therefore relatively low. Amount of PW increases with production age. Gas fields are expected to produce significantly less water than oil fields.

3.4.1. PRODUCTION CHEMICALS

Chemicals are added to the production system to ease the process, precent scale or minimise corrosion in different parts of the process. A “chemical cocktail” is continuously injected to the three templates consisting of:

- MEG,

- pH-stabiliser,
- Corrosion inhibitor, and
- Scale inhibitor.

MEG is constantly injected to the wellheads to prevent formation of hydrates. Hydrates are ice-like solids of gas trapped inside the lattice of water molecules. They are stable at low temperatures around 20°C and moderate pressure challenging flow assurance in pipelines of deep waters. Formation of hydrates slows down the flow, and hydration plugs have potential to block the pipeline. Well flows in offshore pipelines are cooled by heat exchange with the sea water (Seo & Kang, 2012). With longer pipelines follows an increase in the potential of hydration plugs. By adding MEG to the well stream, the hydrate curve is shifted towards the left (Figure 9). This way, flow assurance is secured at temperatures down to about 6°C which is close to the average temperature of the sea water.

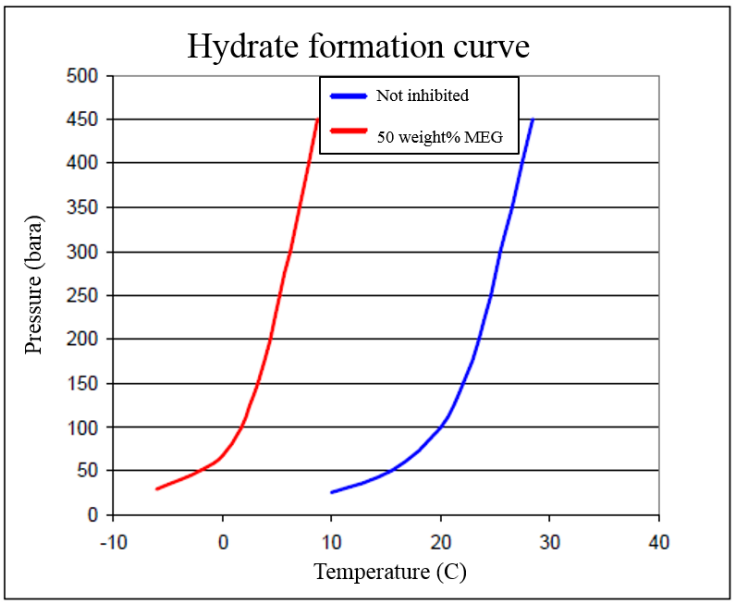


Figure 9 - Hydrate formation curve for the Vega production. Modified with translation from description of system 46, Monomethyl glycol (MEG) injection, provided by Neptune Energy Norge AS (2014).

The constant injection of MEG leads to an uncommonly high usage level of MEG. The alternative was chosen to due to the long tie back to host platform giving high risk of hydrates. Injected ratio between MEG and PW must be 50/50. With the current production rate of PW, these are volumes that the MEG equipment at Gjøa can handle. The average use of MEG on Vega today is about 6 m^3/h. MEG is on the PLONOR list and is therefore allowed to be discharged without special permission.

A corrosion inhibitor is injected to minimise corrosion of the pipelines. Dissolved CO_2 in the water reduce the pH and promote corrosion by preventing protective films to form. Being made of carbon steel the pipelines are highly potent to corrode and large damages can be done in only a couple of hours.

A pH-stabiliser is also injected to minimise corrosion of pipelines and equipment against CO_2 rich gases as well as organic acids following the PW. Stabilisation of pH is based on increasing the pH resulting conditions favourable in formation of protective product films of iron carbonate (Olsen & Halvorsen, 2015). Use of pH-stabiliser is recommended to use only in pipelines with condensed water. In case of produced formation water with calcium, a high pH lead to formation of scale.

A scale inhibitor is injected to prevent solids of $CaCO_3$ from precipitating and possibly blocking pipelines and/or equipment. $CaCO_3$ form as a reaction between CO_2 in the well stream and calcareous water. Scale inhibitor is injected due to addition of the pH-stabiliser.

Additional chemicals are injected discontinuously for different situations, listed below.
An emulsion breaker is added to the separator as stable emulsions of oil and water may follow the well stream. Emulsions are tiny droplets of one phase inside the other making separation of oil and gas difficult. By adding an emulsion breaking chemical, the stability of occurring emulsions is reduced, and a more efficient separation of the two phases is achieved.

A H_2S scavenger is injected to Vega 1st stage separator for lowering of the H_2S concentration in the well stream when produced gas contains H_2S. H_2S has corrosive characteristics and an export specification of 2.5 ppm that needs to be achieved before transport.

A wax inhibitor is injected to prevent wax from forming in condensate and oil when cooled by lowering the wax forming temperature. The wax inhibitor is injected during planned production stops.

3.4.2. GJØA CHEMICALS ALLOCATED VEGA PRODUCTION

Chemicals added to the Gjøa production and treatment from Gjøa 2nd stage separator are partly due to Vega production. Hence, portions of the discharged chemicals can be allocated the Vega burden by allocation keys.

Biosides are injected to inhibit algae and bacterial growth by poisoning in storage the tanks for diesel and open drainage water on the platform. Most of the electricity required by Vega and Gjøa is provided from onshore. The diesel is for generating electricity for emergency generators and a small part of platform operations.

An antifoam is injected to Gjøa 1st, 2nd, and 3rd stage separators to prevent foam from forming. Formation of foam reduces the effectiveness of the separation and might even cause foam to follow the gas. Antifoam chemicals reduce the surface tension in the liquids phase leading to a reduced ability to form bubbles.

A triethylene glycol (TEG) is injected to extract water residue from the gas. Gas from Vega 1st stage separator and Gjøa 1st stage separator is led through gas treatment, system 24. It is important to dry the gas to prevent hydrates from forming in the export pipeline.

Possible allocation procedure is further described under the methodology chapter, 5.3. An overview of where and which chemicals are used for each of these processes and are presented in Table 3.

Table 3 - Overview of chemicals injected to Gjøa process that can be allocated Vega production, including which part of the process the chemical is added. TEG = Triethylene glycol.

Part of process	**Chemical function description**
Gjøa 1st, 2nd, and 3rd stage separators	Antifoam
	Demulsifier
Gas treatment	Gas treatment (TEG)
Oil export pipeline	Corrosion inhibitor
Oil treatment	Wax inhibitor
Diesel and drainage tank	Biosides

Close to all the PW from Vega is separated from the hydrocarbons in the Vega 1st and 2nd stage separators. A small amount of additional water is separated from Vega condensate over the Gjøa separators and is led though the water treatment facility. Expected volumes are too small to make a significant contribution to calculated discharge volumes. Hence, chemicals added for water treatment is not allocated Vega but have been included in the inventory for a better understanding and overview of total discharge of both installations. A Flocculant is injected to the hydrocyclone and floatation units in system 44 for Gjøa PW. The purpose is to promote formation of larger droplets of oil making then easier to remove from the water. Scale inhibitors are added to oil and gas inlet manifolds. Three different scale inhibitors are added for Gjøa production, from separate storage tanks. A wax inhibitor is added through pipelines to subsea wells. Both the scale inhibitors and wax inhibitors for Gjøa production had different trade names than those for Vega.

3.4.3. HAZARDOUS WASTE

Waste from Vega consist of residual chemical and salt drained from the MEG treatment system to storage tank 67TB051A. Roughly every three months, it is then pumped and transported by a vessel to an onshore waste facility, SAR (former SpesialAvfall Rogaland AS). It is the waste treatment facility that onward is responsible for handling the waste. A large portion of the total waste from Gjøa semi-submersible originates from the MEG treatment system. From 2015, Neptune decided to separate the MEG waste report from the residual waste.

Wash water from cleaning of the MEG regeneration facility has been sent onshore for destruction until September 2015. After this, water pumped out after first wash is still sent for destruction while water from the second wash is discharged to sea. The difference in handling of the waste chemicals have affected the discharge factor.

3.4.4. WELL INTERVENTIONS AND SUPPLY VESSELS

A well intervention is any work performed on an oil and gas well after start of production for maintenance of the well or damage repairs. Amount of used and discharged chemicals (in kg) trailing interventions are reported for Vega and included in the quantification of total discharge. Supply vessels transport production chemicals out to the Gjøa semi-submersible. Other vessels are also used to transport waste generated from the MEG facility back onshore.

3.5. Environmental monitoring of the study area

Before start of production, mandatory field monitoring of background levels was measured in a baseline survey. Surveys were performed individually for both Vega and

Gjøa in 2007 (Uni Research Miljø (SAM-Marin), 2014). Another monitoring survey for the studied area was performed in 2014, covering oil and gas fields in the North Sea region IV (Uni Research Miljø (SAM-Marin), 2014). Latest report is from 2017 of monitoring of the same region performed by Akvaplan niva (2017). It has not been published yet but is available internally at Wintershall. Samples of total hydrocarbon concentration (THC), total organic matter, metals, and sediments were taken and analysed in addition to monitoring of the biota. All results were compared to background levels. For both Vega and Gjøa, it was concluded that the biota remained undisturbed. Barium concentrations were above limit of significant contamination (LSC) for 8 measuring stations at the Vega field. Metal levels were generally higher in 2017 than from the previous surveys but was concluded not possible to connect to the historical discharge. At the Gjøa field, concentrations of chromium, sink and copper were above LSC at three different stations. For the average results, all concentrations were below LSC except for led in 2014. In 2017 it was found that concentrations remained unchanged or lower compared to last analysis. Average results for both Vega and Gjøa concluded that the biota at none of the monitoring stations had been affected by the producing installation yet.

All operators of new developments on the NCS are required to include a calculation of the EIF in the preliminary impact assessment. EIF reports were provided by Neptune for total discharge from Vega and Gjøa. EIF calculation based on discharge reported in 2013 gave a value of 3.9. The latest EIF calculation gave a result of 8 based on discharge from 2016. All values are below the threshold value of 10, meaning that the risk for environmental impact is considered to be low. A new simulation will have to be performed with change in production chemicals.

4. CASE STUDY: PREDICTED EIF WITH OPERATIONAL CHANGES

An aging production well is expected to produce more and more water. Today, MEG is currently injected with a ratio of 50/50 to PW. The limit of water production for topside regeneration facility is 10 m^3 of formation water and 100 m^3 of condensed water per day. Predicted volumes of saline formation water will at a future point exceed the capability of the MEG regeneration facility. Initial plan for production of Vega was to shut down any well that started to produce water. With a currently higher focus on increased recovery of reserves, water will also have to be produced.

Wintershall has investigated scenarios with different operational changes as a response to this impending challenge. Avoidance of hydrate formation will continuously be the main issue during unexpected production stop. Pipeline temperature during normal production is 20℃, which is above the hydrate curve. During shut-down, temperature will be lowered until equal to sea at 6℃. Hydrates may form at this temperature when water and gas is mixed. During stops water and gas are in separate phases resulting in no problems. It is when production is restarting and the two phases mix that problems initiate. As the chemical aiding to avert hydrates must be removed, there are three variable adjustments that can avoid hydrate formation and plugging of the pipeline:

1) increase in temperature,
2) reduction of pressure, or
3) introduce new chemical that requires a lower injection ratio to water than MEG.

Operational changes are planned over four steps. To control temperature, major changes will have to be done with the pipelines such as insulation. The option is considered

impossible due to costs in gross disproportion with expected benefit. Pressure is the only variable that is possible to control currently without any equipment modifications. During a stop, the pipeline can be depressurised by flaring of gas. It is an emergency procedure that is included in the original operation plan. Change of different production chemicals are the basis of the three next steps. This case study investigates step 2, where MEG will be replaced by a kinetic hydrate inhibitor (KHI) which has an injection ratio of 2-4% to water. KHI works by reducing the speed of which hydrates form. Depressurisation with flare will still be implemented during longer stops. A negative side of using KHI is that hydrates that form after the given time will be more difficult to melt. Decreasing of pressure is the initial approach of melting hydrates while pigging is another more time-consuming solution. Step 3 and 4 in the operational change plan involves two new chemicals that will discontinue the solution with flaring. These chemicals are not available on the market yet, being the reason for the selection of KHI to be injected primarily even if only effective over a limited time.

The corrosion inhibitor will be the only additional injected production chemical to the KHI. MEG promotes formation of NaOH that increase the pH in pipelines. High pH leads to scale, which is the reason for injection of scale inhibitor. The pH-control is only added due to injection of scale inhibitor. Without continuous injection of MEG, both scale inhibitor and pH-control are removed from the production chemical mix. MEG will still be injected during planned shutdowns in addition to wax inhibitor. Usage of wax inhibitor is expected to increase due to:

1) facilities aging, which call for more frequent planned shutdowns,
2) low production rate from Vega South, in which case the temperature upstream Vega Central template may fall below the wax appearance temperature.

By changing the chemical composition, the MEG regeneration facility will be taken out of service. This change in process will further affect the discharge factors of all Vega production chemicals and should be considered for the estimations of future discharge. Vega 2nd stage separator is planned to be connected to Gjøa's water treatment system and go overboard with Gjøa PW. Another tie-in installation is additionally planned and will most likely have started producing by 2021. This installation will contribute to a PW volume even higher than current expectations only including Vega and Gjøa lowering the discharge concentrations of both natural components and chemical additives.

5. METHODOLOGY

An increasing amount of publications evaluating various processes and products are published. Using an already existing model is most common when performing a LCA. No already existing LCA models were used for this study as resources were limited to available software at Wintershall. Quantification of environmental footprint and modelling were performed in Microsoft®. Excel 2016. DREAM simulations of three different EIF scenarios that were ran at the International Research Institute of Stavanger (IRIS).

5.1. Following a standard for development of the model, ISO standards

When developing a new model, it is desirable to follow already established guidelines that describe boundaries and data requirements. Using credible guidelines also provide better validation of results. Researching publications of LCA, the most recognised approach was to follow the ISO standards 14040-14044 from 2006. ISO 14040 describes principles and framework for life cycle assessment. ISO 14044 specifies requirements and guidelines for LCA under environmental management. Mitchell and Hyde (1999) state that the LCA standards from ISO provide a good basis for development of new LCA tools or implementation in industry. In addition, they mention that these standards are generic guidelines and do not provide industry specific description of recommended methodology.

Another set of guidelines is the Product (P) and Organisation (O) Environmental Footprint, PEF and OEF prospectively, published by the EU Commission in 2013. The aim of these two new guidelines was to harmonise other previous existing guidelines for

easier communication and comparison of results. The PEF/OEF was early criticised for counteracting their initial intention introducing new terms in addition to bringing yet another set of guidelines to the market (Finkbeiner, 2014). Today these guidelines are still considered to be under development (Finkbeiner, 2016) and were subsequently not further considered as choice of methodology for this thesis. The methodology for the following work is based on the ISO 14040-14044.

5.2. Data collection

Data collection has been described as a tedious and comprehensive process (Rebitzer et al., 2004; Yang et al., 2016). It is common to use existing online databases such as Gabi, or Ecoinvent to retrieve necessary data to perform a LCI as real data is often not available (Yang et al., 2016). These data are composed of generalised numbers from secondary sources, using them adds uncertainty to the results (Smit et al., 2009). Working with Wintershall, with cooperation from Neptune providing access to internal databases, it was decided only to use available real data.

Updated discharge data are submitted to Environmental Hub (EEH), each year. EEH is an online portal where all operators on the NCS upload their emission and discharge numbers and have access to see what other operators report. EEH was initially the preferred source of data as numbers from all fields are available for anyone with access. It was concluded later that the data available on EEH were not sufficient as Vega specific numbers were not possible to acquire. No discharges from subsea installation production are reported from the field in EEH, only included in the discharge reported from Gjøa. NEMS Accounter is a more detailed online portal where operators only have access to

their own discharge data. Data from well interventions on Vega are available with Wintershall access to NEMS Accounter. With Gjøa access provided by Neptune it was possible to separate discharge of PW and production chemicals between the two installations. EEH was continuously used for validation of numbers of as this is where official numbers for production data are retrieved by the NPD.

5.3. Allocation keys

The ISO 14044 (2006) explains that whenever a process produces more than one product, the environmental burden must be allocated the products respectively. The standard follows with that allocation key procedures should be based on physical relationships as long as possible. Vega and Gjøa production share some production chemicals. Allocation keys were calculated to partition the output of these based on the physical relationship of produced volumes (Table 4). The goal of the allocation was to identify how much of the total environmental burden should be on Vega and how much on Gjøa. Production chemicals only injected for production of one field were allocated the given field, and specific for each year. Calculated allocation keys were applied to the chemicals included in Table 3.

For calculation of chemicals injected to the total wellstream, it was assumed that ratio of chemicals used in Gjøa 2nd and 3rd stage separation was equal to the ratio of production rate from each field, given in total produced volumes, $V_{total}\ (Sm^3)$. Vega contribution to the burden was then found using volume of Vega, $V_{Vega}\ (Sm^3)$ over total produced volumes. Allocation key for gas treatment chemicals was found based on gas production volumes from Vega, $V_{gas}\ (Sm^3)$, over total gas production, $T_{gas}\ (Sm^3)$. Condensate from

Vega follows the oil treatment topside Gjøa. Oil treatment chemicals allocation key for Vega condensate production, $V_{oil}\ (m^3)$ was therefore based on production volumes of both oil and condensate, $T_{total}\ (m^3)$. The unit m^3 was used in the model as it was the unit volumes were reported in the retrieved data.

Table 4 - Listed allocation keys for production chemicals common for both Vega and Gjøa production stream. Includes description of what parts of the process the different keys are used for as well as showing the calculations.

Part of process where chemical is added	**Allocation key (Ak)**	**Calculation**
Gjøa 2nd and 3rd stage separators Diesel and drainage tank	Ak_{total}	$Ak_{total} = \frac{V_{Vega}(Sm^3)}{V_{total}(Sm^3)}$
Gas treatment Gas export pipeline	Ak_{gas}	$Ak_{gas} = \frac{V_{gas}(Sm^3)}{T_{gas}\,(Sm^3)}$
Oil treatment Oil export pipeline	Ak_{oil}	$Ak_{oil} = \frac{V_{oil}(m^3)}{T_{oil}(m^3)}$

5.4. Life cycle thinking approach for assessing discharge to sea

All criteria for a full LCA were not met conducting this study. DREAM provides the best estimate available to assess the environmental hazard caused by discharged PW. However, the DREAM model only accounts for selected constituents in PW. Other local sources such as runoff water, waste discharge, and vessels are not included in the model (Durell et al., 2006). To achieve a comprehensive and holistic assessment of the production, it was decided to follow a life cycle thinking approach. Main framework for LCA by the ISO 14040 (Figure 1) was followed as close as possible. All discharge with available data was included in the inventory analysis. Components included in DREAM

followed the framework though the impact assessment. Interpretation could be done mainly for the results of the DREAM simulation but some also for discharged amount of chemicals regarding the production process. Application was left for Wintershall to decide. The results of this work should make it possible to identify where the largest contribution to the environmental burden lies highlighting areas of most interest for environmental decisions.

5.4.1. GOAL AND SCOPE DEFINITION

The goal of this work was to assess the environmental impact of Vega and locate areas of improvement. Investigating the whole life cycle of the gas field was narrowed to focusing on the production phase due to the time constraint. A general value chain for the petroleum industry is presented in Figure 10. It is evident that production represents only one of seven large phases. Knowing that PW is the largest waste stream, it can be argued that it provides the most representative phase for a limited study such as a master's thesis.

With the described scope, this work can be defined following a 'cradle-to-gate' approach. The reservoir and the export pipelines are physical boundaries for the modelling. Functional unit was set as produced volume (m^3). Discharge to sea relative to yearly production of the functional unit was calculated. Geographical area includes an area around Vega and Gjøa limited in DREAM with the parameter size of habitat grid. Total technical system of Vega is extensive. Directly relevant components of the process were described in section 3.3. Boundaries were set partly based on available data. Intended audience was Vega production department and the HSE department at Wintershall.

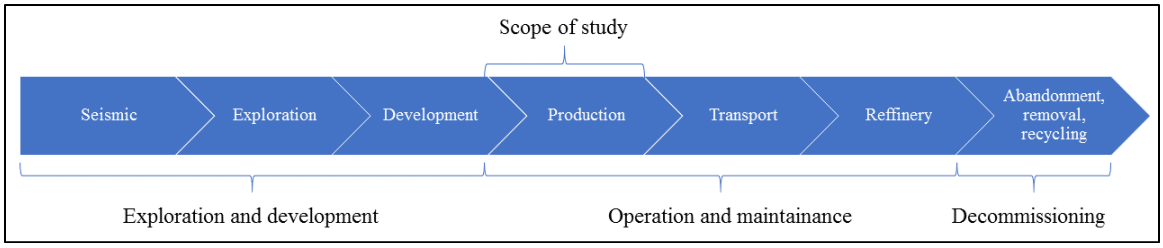


Figure 10 – Value chain or life cycle of upstream and production phases in the petroleum industry. Scope of this study marked at the top of the figure. Modified from DNV GL AS (2015).

5.4.2. INVENTORY ANALYSIS

The inventory was based on sources with direct contribution to discharge described in section 3.4. Figure 11 presents the complete inventory of the Vega production process system. Input and output streams related to this study are chemicals, PW and hydrocarbons. The system of highest focus is included in the dashed square in the lower right corner. Only real data were used for the inventory, slightly limiting the holistic picture as data were not available for all aspects.

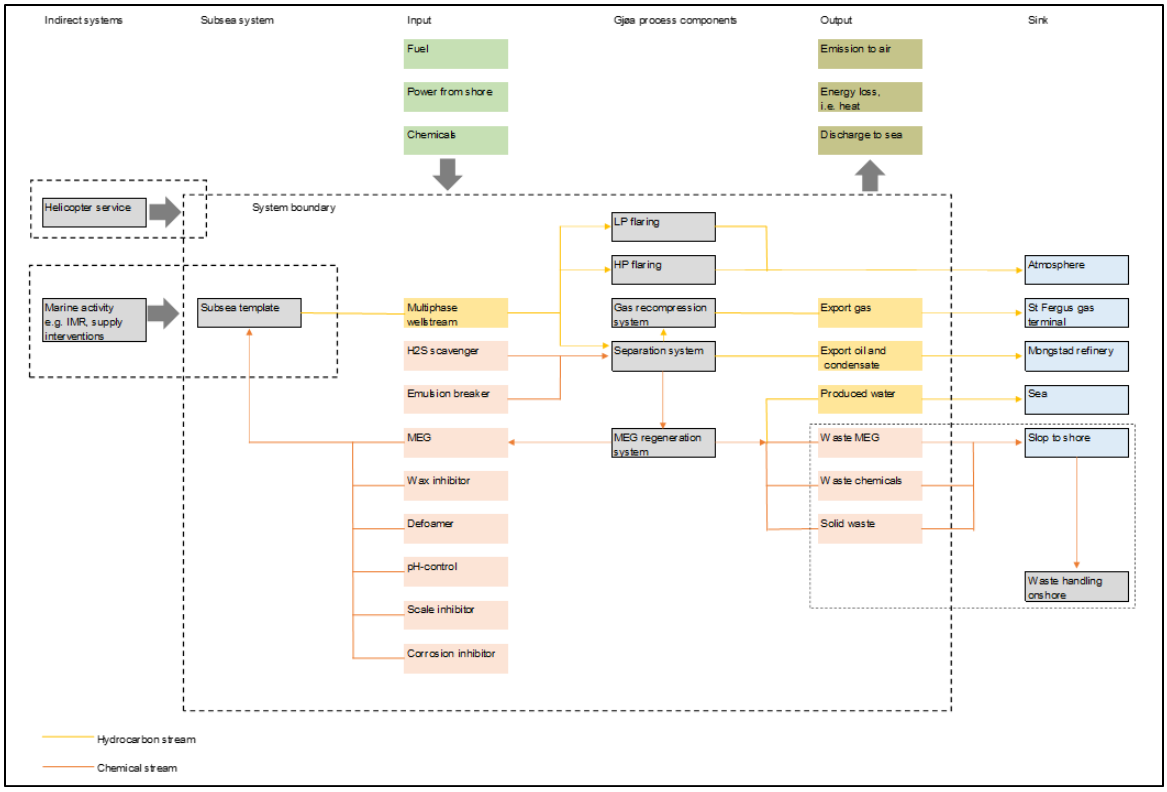


Figure 11 - Overview of total input output inventory analysis for the Vega production process. Made in cooperation with Fløysvik (2018).

5.4.2.1. Vega chemical consumption and discharge, cumulative

Which chemicals in the production process could be allocated Vega production were found researching and comparing chemicals listed in NEMS Accounter, EEH, and the system descriptions of chemical injection, MEG injection, and MEG regeneration facility. Chemicals used and discharged were listed in terms of kg for every year from start of production in 2010 until 2017. A complete mass balance calculation is available for the operator in NEMS Accounter. Portion of a chemical not reported discharged can either be injected, exported, or sent to onshore disposal. No chemicals are reinjected at

neither Vega or Gjøa. Exported means they follow the produced hydrocarbons in the export pipelines.

5.4.2.2. Hazardous waste

Waste reports from the MEG regeneration facility SAR were made available by Neptune from 2015, 2016 and 2017. Over three years, produced waste (kg) have been categorised as hazardous waste under “Tank cleansing waste”, “Solvents” and “Chemicals”. Fate of waste is classified as recycle (kg), energy recovery (kg), or landfill (kg) in NEMS Acconter.

5.4.2.3. Well interventions and vessel operations

Discharges from mobile units during well interventions and transportation of chemicals and waste by supply vessels were investigated. Chemicals discharged during interventions the only discharge included in the Vega annual environmental reports during normal production. Description of events were retrieved from the reports while data were retrieved from NEMS Accounter for Wintershall.

Discharge during transport was of interest to include all sources of discharge to sea. Volumes of discharge from vessels are considered small and released along the entire travel route. Contaminants (dispersed oil) will be of low concentrations and quickly dilute to levels close to background concentrations. Reports of any discharge from these operations are reported under marine operations and is not available for the operator of the producing fields. The contamination due to vessel operations was considered small enough to be ignored.

5.4.3. IMPACT ASSESSMENT

The impact assessment aims to describe the environmental consequences of gas and condensate production from Vega. Output from the inventory analysis was to be translated into consequences or impact categories, defined as classes representing different environmental areas of concern assigned to outputs of the inventory analysis (ISO 14040, 2006). Discharge to sea cover toxic impact on marine aquatic organisms. Impact factors of ecotoxicity have been assigned different descriptions: marine aquatic eco-toxicity potential (MAETP) (Guinée et al., 2002; Stamford & Azapagic, 2014), and comparative toxic unit for ecosystems (CTUe) (Ling-Chin & Roskilly, 2016). Calculated equivalent for measurement of toxicity potential is 1,4-dichlorobutane (DCB) equivalent for both. A clear definition of DCB equivalent and a presentation of calculations were however difficult to retrieve. DREAM and the EIF were instead used for the impact assessment. Main arguments were that it is already a well-established and regulatory method for assessing water discharge to sea on the NCS. Discharged components or substances that were not included in the DREAM model were not converted into impact categories, hence only included in the LCI.

5.4.4. INTERPRETATION AND APPLICATION

Results were seen in the light of the scope set for the assessment and to try to identify areas for improvement. Discharged components not included in DREAM were presented in graphs, included in the results section 6, for an overview of all potential sources of environmental impact. With the quantification of total discharge, potential effect on the environment could further be discussed. The interpretation and application of this study is included under section 7.

5.4.4.1. Evaluation of result robustness

Evaluation is a part of the interpretation phase of LCA and should be done for completeness, check, sensitivity analysis, and consistency check according to the ISO 14044 (2006). Available forms for evaluation were retrieved from the guidelines and modified to fit the field and scope of the study.

A Completeness check was performed based on to ensure that no large contributors were left out of the study. All phases in the life cycle were included. Those outside the scope were commented on what is required to find the data. A **consistency check** was performed to evaluate the data in terms of the goal and scope of the study. The check was performed based on the consistency check available in the ISO 14044 (2006).

For the **sensitivity analysis**, the most decisive factors for the results in this study were identified as the allocation factors. These were calculated based on production volumes. The database also provide data on energy (MJ) from each production stream which could be argued to allocate portions of environmental burden to each installation in a more representative matter. Different sources of production data (NEMS Accounter, EEH and NDP) provide different numbers. The ISO 14044 (2006) states that whenever there are several options for allocation procedures, a sensitivity analysis should be performed on the consequence of allocation. It was therefore of interest to measure the sensitivity of the allocation keys depending on different reported data.

5.5. DREAM simulations

The DREAM simulations were performed at IRIS. Model parameters for the habitat grid was 15 km x 15 km and concentration cell size was 50 x 50 x 5 m. This setup

corresponds to a small release or discharge in the EIF computational guidelines (Norsk olje & gass, 2003). Specific data from Vega-production were acquired for 2013 and 2016, corresponding to EIF calculations already performed for the total discharge. Results from new calculations were compared with the old simulations for estimation of Vega contribution to environmental impact. It was assumed that the results would show a slightly lower calculated EIF as the new simulation was only for one contributor of the total discharge. Only slightly lower as it was already known that Vega production chemicals have a large contribution to total EIF. Total input datasets are given in Appendix 2.

5.5.1. INPUT DATA: EIF FOR COMPARISON WITH GJØA

Input data for DREM consist of natural components and chemical additives. Concentrations of natural components in the PW were acquired from the database. Samples of PW are sent to a laboratory for analysis two times per year. Input concentration for each component per year is the sum of calculated concentrations weighed on the validity of laboratory samples and the daily measured PW volume.

$$Input\ concentration\ for\ DREAM\ model\ \left(\frac{mg}{l}\right) = \frac{\sum_{i=1}^{n} V_i C_i}{\sum_{i=1}^{n} V_i} \times 1000 \qquad (2)$$

Where:

V_i = volume (m^3) of discharged PW on the i^{th} day, and

C_i = concentration (g/m^3) of component on the i^{th} day calculated by the valid concentration from last sampling date.

Volume of discharged PW is measured every day and uploaded automatically in the database. Laboratory analyses of PW is performed two times per year. Based on these

results, concentrations are given with a validity. These analysed concentrations are further used to find daily mass of each component (kg) before reaching daily concentration (kg/m^3) for accumulated values (Acc.).

$$\frac{Volume_{daily}\ (m3) \times Concentration_{valid\ for\ exact\ day}\left(\frac{g}{m^3}\right)}{1000} = Component\ (kg) \quad (3)$$

$$\frac{Acc.component\ (kg)}{Acc.volume\ (m^3)} \times 1000 = Concentration_{year\ X}\ (kg/m^3) \quad (4)$$

Concentrations for the Vega PW stream were retrieved from the database and recalculated for correct concentration in the total PW volume. Corresponding PNEC values for every natural component were acquired from NOROG's EIF computational guidelines (Norsk olje & gass, 2003).

Discharge volumes of chemical additives were collected from the developed inventory analysis. Concentrations of chemical were calculated by discharged amount (mg) of every chemical over the total PW volume (l). Chemical and toxicological information for added chemicals was retrieved from the HOCNF form of each product. Components were numbered rather than named to maintain the anonymity of the chemicals. "EIF computational guidelines" emphasise that the most conservative values from HOCNF should be selected for input (Norsk olje & gass, 2003). For best comparative results for Vega contribution, components for input chemicals were chosen to correspond to those included in Gjøa report. Percentages of composition contributions were back calculated from input data in Gjøa report for input for Vega simulation.

5.5.2. INPUT DATA: ESTIMATION FOR CASE STUDY

Expected Vega PW volumes were estimated internally at Wintershall to be 106 303 m^3 in 2021. Total volumes were estimated to 421 140 m^3, provided by Neptune. These values are given with large uncertainties as for every other estimation of remaining volumes of water in a reservoir. Information of expected PW from the added installation was not available. Investigating the data, it was noted that expected volumes of PW calculated by Wintershall and Neptune most likely were based on different assumptions. Gjøa predicted volumes of water is decreasing rapidly from 2019 while Vega is increasing. This is not the trend that is normally expected for production fields as it is more typical that volumes of PW increase with age. It is likely that Gjøa have not considered the expected PW volumes coming from Vega, but kept the current limitations or restrictions on to the MEG facility. It can also indicate that formation water from Gjøa is not included (only condensate water) or that some wells are planned to be shut down. The prediction is not including the planned tie-in field either as it is classified as "contingent resources" by the NPD resource classification meaning the host platform is not yet required to account for these volumes in their predicted numbers (Norwegian Petroleum Directorate, 2018c). Based on these uncertainties, it was of interest to also run a revised simulation with a doubled volume of PW.

A conservative estimated for start of KHI injection was set to be 2021 based an internal document of predicted PW volumes from Vega showing this year as when the MEG regeneration facility will be out of capability. Assumed discharge volumes of KHI and corrosion inhibitor were calculated based on properties of the chemical found in NEMS Chemicals and the HOCNF. See Appendix 3 for complete calculations of usage and discharge amounts (kg). Volume of wax inhibitor to be discharge was assumed to be

equal to the highest historical discharge volume from what has been reported since production start, 808.75 kg.

Gjøa chemicals used in 2021 were assumed to be equal to chemicals used in 2017 as no other information was available. Chemicals added to the Gjøa process, allocated Vega production stream were set to be the same amount in kg as for 2017. Concentrations were recalculated with the assumed volume of PW.

5.6. Uncertainties and assumptions

A model is a simplified version of the truth. Some larger uncertainties and assumptions had to be made during the work on this study. These are included and described here.

Although aware of possible large uncertainties, reported and expected numbers are assumed to be true values. For discharged chemicals, discharge factors are calculated and applied for estimations of discharged amount. Analysis are not taken for the chemical additives when analysing PW in laboratories. Expected PW volumes for Vega and Gjøa in 2021 is given with especially large uncertainties. The longer the future perspective, the more uncertain the estimated numbers. Calculations and estimations are the best approach available for quantification of the discharge.

Gas and condensate led from Vega 1st and 2nd stage separators are extracted from yet some water that will follow the Gjøa water cleaning facility. The volumes were assumed small enough to be neglectable.

Production data retrieved from NEMS Accounter were assumed to be correct even aware of official data from NPD differed. Production data were reported with different numbers in EEH additionally. The assumption was made as a choice of database had to be taken. Already using NEMS Accounter as database for discharge data, it was decided to also use these production data for better correlation between the data. A sensitivity analysis was performed on how the change in production data affected the change in allocation and hence the amount of chemicals allocated the Vega burden.

For the calculation of allocation keys, oil and condensate volumes were given in m^3, and gas in Sm^3. For the calculation in this thesis it is assumed that the given volumes in m^3 are equal in standard conditions. Finding mass given produced hydrocarbon stream, NEMS Accounter use the equation:

$$Mass\ (kg) = Volume\ (m^3) * Density\ (\frac{kg}{Sm^3}) \quad (5)$$

It implies that the volume at measurement conditions (m3) is equal to the volume as standard conditions (Sm^3). Standard condition is defined as temperature of 15°C, and pressure of 1 kPa (Schlumberger, 2018). Gas, and most liquids, expand with increased temperature and/or decreased pressure. Given volumes in m^3 may be higher in Sm^3 than the assumption made express. No information on measurement conditions however make it impossible to calculate accurately to standard conditions. Given the calculations in NEMS Accounter, these volumes were assumed to be equal for both oil and gas.

NEMS Accounter reported energy (MJ) from Vega condensate in 2013 was assumed to be wrong and further recalculated. Net calorific value (MJ/Sm^3) was assumed to be the

same as the following years (= 38 500 000) which differs significantly from the reported value of 40 400.

6. RESULTS

Presented results are from inventory analysis performed in Excel and DREAM simulations ran at IRIS. Full data sets from the inventory spreadsheet are included in Appendix 4.

6.1. Inventory analysis

Based on the scope for this study, the inventory analysis has the main focus on production chemicals as constituent in PW as this included most available data. These have been gathered from both Vega and Gjøa. Chemicals from well intervention activities and natural components in PW have been collected for Vega. Amount of produced waste has only been included from 2015 as separate reports for Vega were not taken out before that year. Natural components of PW have been included, also listed in Appendix 4.

6.1.1. DISCHARGED CHEMICALS

Total used and discharged Vega production chemicals is presented in Figure 12. Only a small amount of total chemicals used is discharged to sea due to the separation of chemicals from water in the MEG regeneration facility. Each column includes all chemicals for comparison of contribution. Not clearly shown in the figure, but retrieved form the cumulative discharge from the inventory (Appendix 4), pH control is the largest contributor with hydrate inhibitor and scale inhibitor following. High discharge rate in 2012 was due to a deviation in the MEG regeneration facility (GDF Suez, 2012). Figure 13 shows the discharge of Vega production chemicals and Gjøa chemicals allocated Vega production. The yellow demulsifier is the allocated portion from Gjøa.

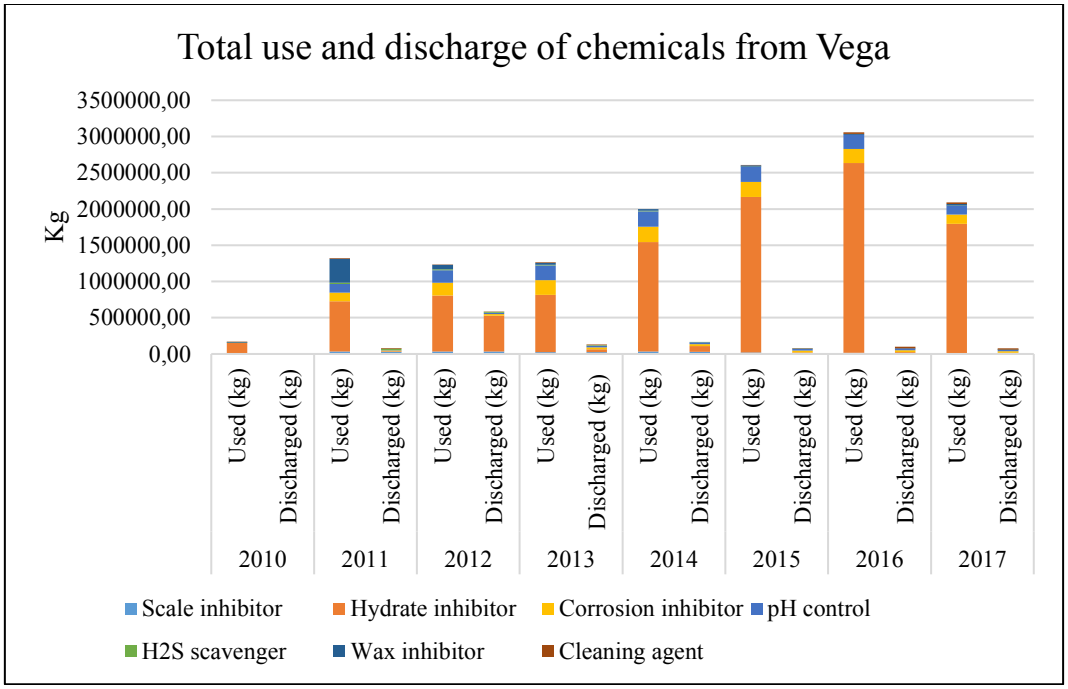


Figure 12 - Use and discharge of Vega production chemicals (kg) from 2010 to 2017.

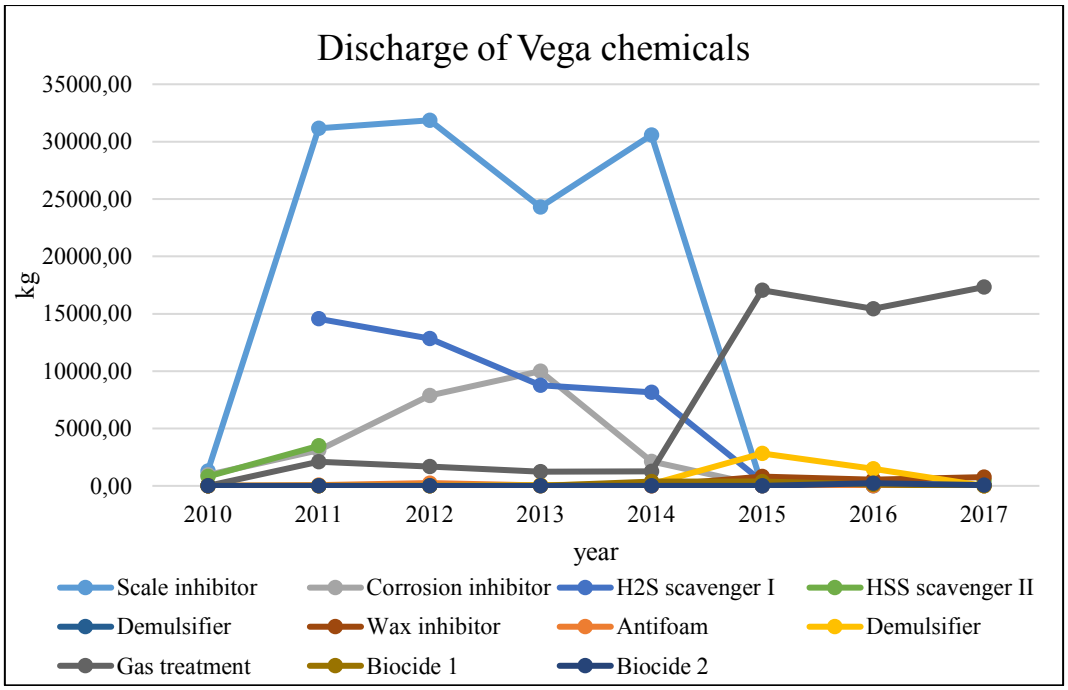


Figure 13 - Discharge of Vega production chemicals and Gjøa chemicals allocated Vega production (kg) from 2010 to 2017.

Portion of colour coded usage of chemicals in percentages is presented in Figure 14. Total discharge has equal distribution between the different codes as Vega production chemicals separate. Black chemicals have been used during interventions, but not discharged.

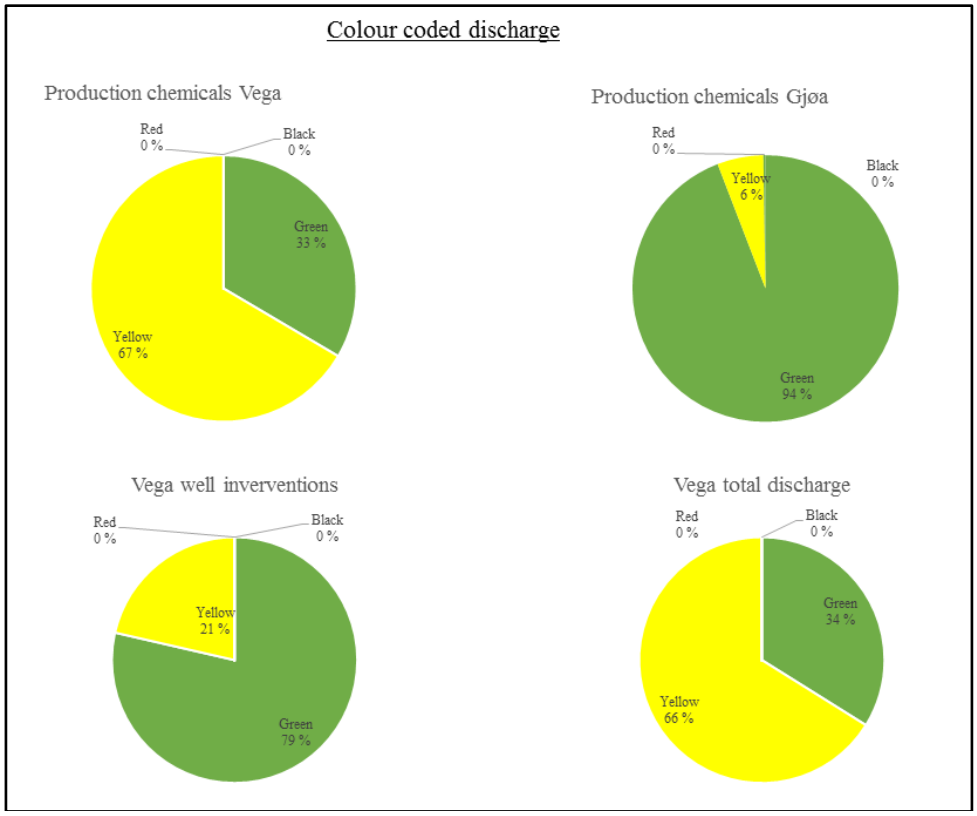


Figure 14 – Portion of amount colour coded chemicals discharged from Vega and Gjøa. Upper left: Production chemicals discharged from Vega. Upper right: Production chemicals discharged from Gjøa. Lower left: Chemicals discharged during well interventions on Vega. Lower right: Total discharge of chemicals (production and well intervention) from Vega.

Discharges with the functional unit of produced hydrocarbons is presented in Figure 15. Water is only visible as short green columns of very small volumes compared to total

production and cumulative usage. Correlation coefficient between cumulative discharge of both production and allocated chemicals, and total production was calculated equal to 0,35. Correlation between cumulative usage and total production gives a coefficient of 0,82.

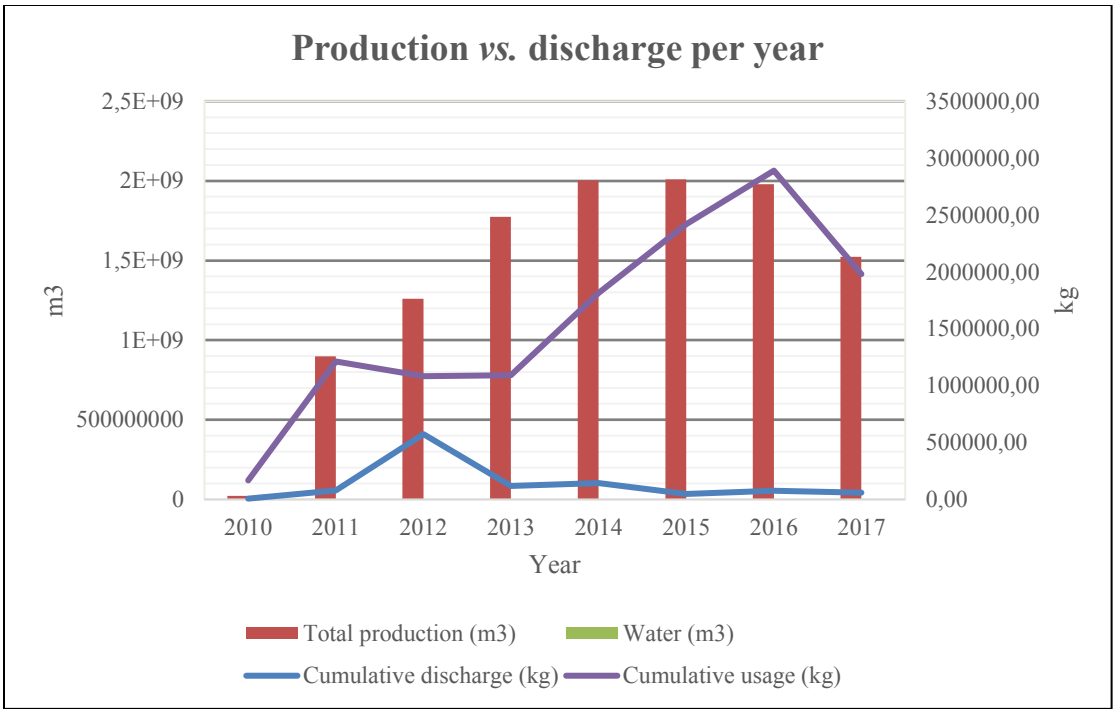


Figure 15 - Total production (condensate, oil, and gas) and water in m3 compared to usage and discharge of chemicals in kg.

6.1.2. PRODUCED WASTE

All registered produced waste that could be allocated to Vega were the hazardous waste from the MEG regeneration facility. All waste from the facility was reported as fully recovered in the same amount of kg corresponding to produced waste (Figure 16). Other waste from Gjøa was in NEMS Accounter reported under the same categories. It was not

possible to allocate Vega produced waste from previous years having only the MEG reports to work from.

Hazardous waste from MEG regeneration facility				
Category		2015	2016	2017
Chemicals				
	Produced waste (kg)	3126905	3456320	2526200
	Energy recovery (kg)	3126905	3456320	2026200
	Recycle (kg)			
	Landfill (kg)			
Solvents				
	Produced waste (kg)		12700	
	Energy recovery (kg)		12700	
	Recycle (kg)			
	Landfill (kg)			
Tank cleaning waste				
	Produced waste (kg)	1980	12528	
	Energy recovery (kg)	1980	12528	
	Recycle (kg)			
	Landfill (kg)			

Figure 16 - Inventory of hazardous waste from the monoethylene glycol (MEG) regeneration facility. Included table is limited to years with data for waste reports.

6.2. Impact assessment by calculation of Vega EIF values

Previous DREAM simulations for the total discharge calculated maximum EIF =17 and time averaged EIF = 8. The largest contributors to environmental risk were corrosion inhibitor component 5 (30 %), BTEX (22 %), and Phenol C0-C3 (18 %). Results from the simulation of Vega contribution to the EIF the same year is shown in Figure 17. Corrosion inhibitor 1 component 5 is the largest contributor with a weight of 77 %. Corrosion inhibitor 1 component 4 and Phenols & alkylphenols C3-C3 were the second and third largest contributors with 10 and 4 % respectively. Biocide 1 component 1 is the allocated Gjøa chemical with the highest contribution to EIF with 3 %. Figure 18 shows the risk picture as a map of the Vega discharge in 2016. Cross sections are also included.

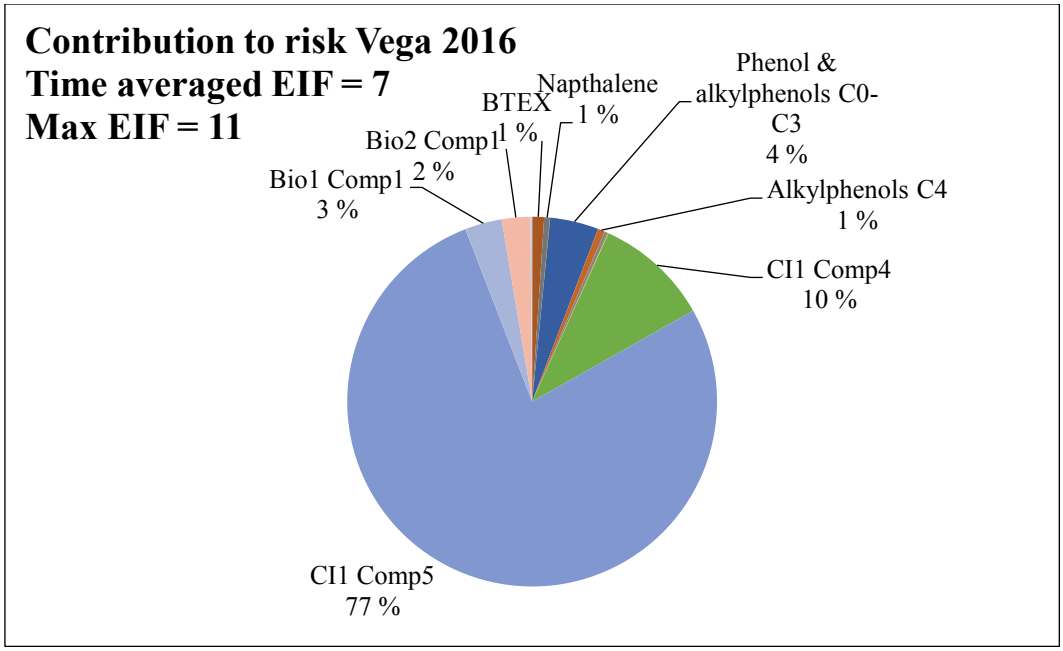
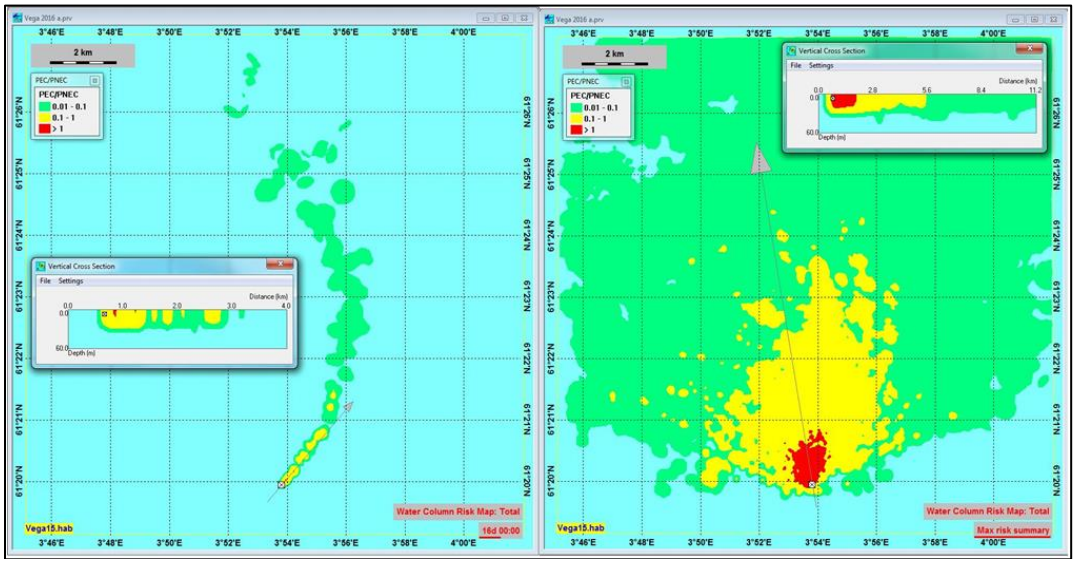


Figure 17 - Pie chart and computed values at time step for maximum risk with contribution from Vega 2016. EIF = Environmental Impact Factor; BTEX = Benzene, Toluene, Ethylbenzene, and Xylene; CI= corrosion inhibitor; Bio=Biocide.



(a) (b)

Figure 18 - Risk map of Vega discharge 2016. Red area is where PEC/PNEC exceeds 1. PEC=Predicted Environmental Concentration; PNEC=Predicted No Effect Concentration. Snapshot of 16h timepoint (a) and max risk summary (b).

With predicted and conservative volumes of PW and chemicals the results of EIF for 2021 gave a maximum EIF = 95 and a time averaged EIF = 43 (Figure 19). Corrosion inhibitor still range as the highest contributor, now with 81 %. As the uncertainties in the PW volumes are so large, a revised simulation was run with a doubled volume halving the discharge concentrations. Revised simulation calculated an even higher time averaged EIF = 44 (Figure 20). Contribution from components by percentage does not change. Figure 21 shows the risk map of Vega revised discharge in 2021. The concentration field is clearly larger than for the simulated discharge of 2016.

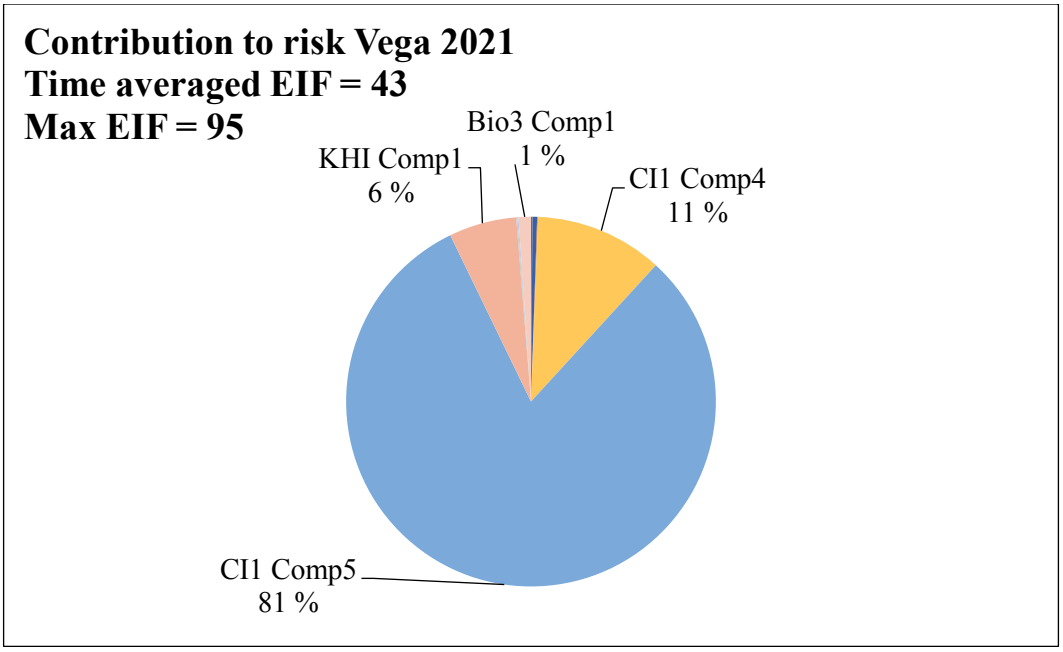


Figure 19 - Pie chart and computed values at time step for maximum risk with contribution from Vega predicted in 2021. EIF = Environmental Impact Factor; CI = corrosion inhibitor; Bio = biocide; KHI = Kinetic Hydrate Inhibitor.

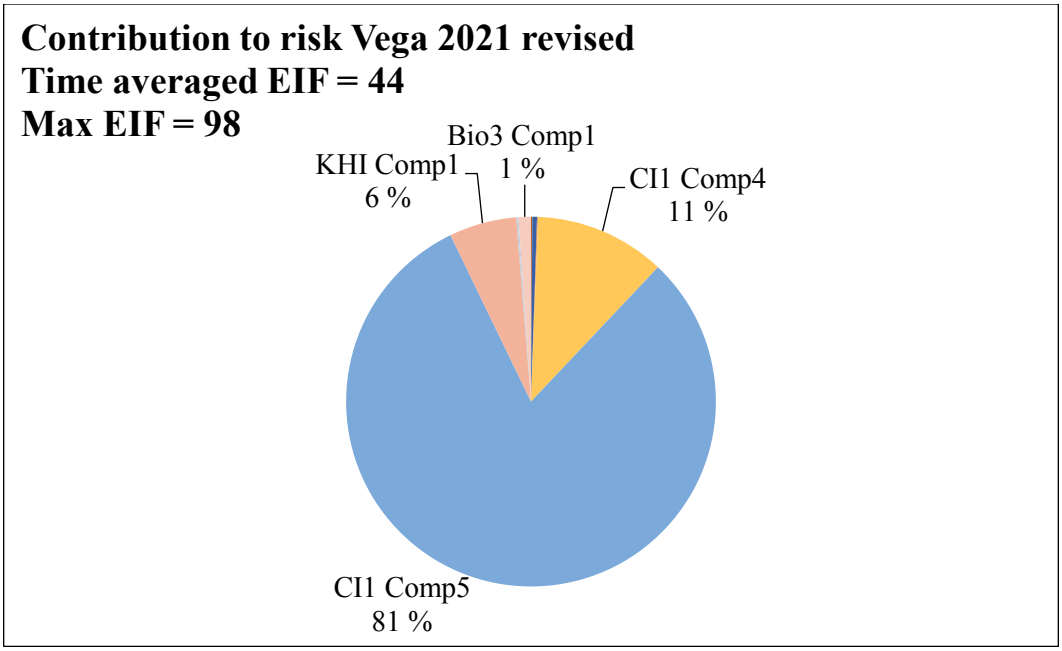
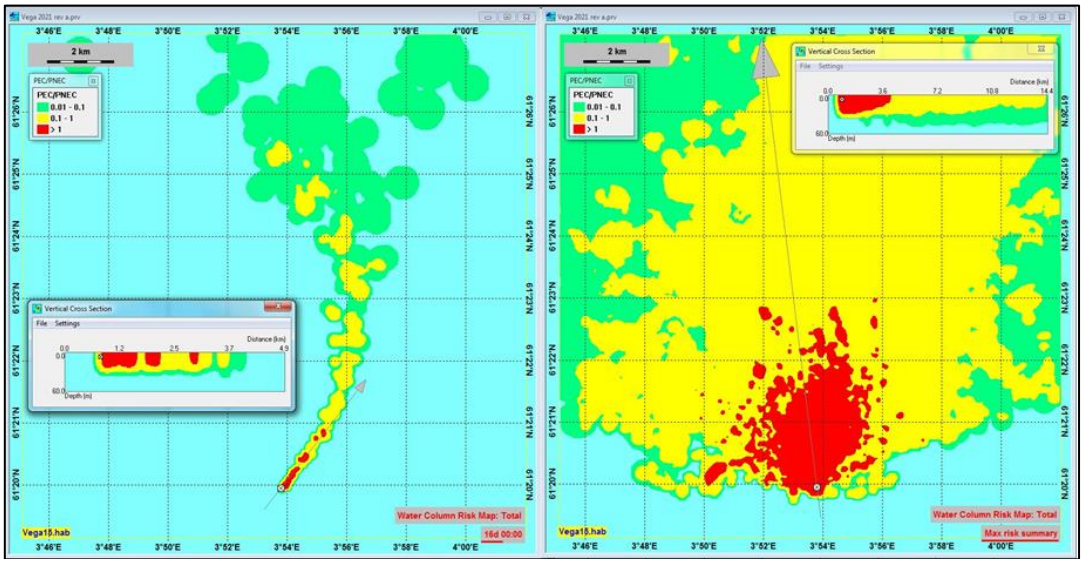


Figure 20 - Pie chart and computed values at time step for maximum risk with contribution from Vega predicted in 2021, revised with double water volume. EIF = Environmental Impact Factor; CI = corrosion inhibitor; Bio = biocide; KHI = Kinetic Hydrate Inhibitor.



(a) (b)

Figure 21 - Risk map of Vega discharge 2021. Red area is where PEC/PNEC exceeds 1. PEC=Predicted Environmental Concentration; PNEC=Predicted No Effect Concentration. Snapshot of 16h timepoint (a) and max risk summary (b).

6.3. Result robustness check after the ISO 14044 (2006)

Results of evaluation elements for determination of reliability and stability of the results. Evaluated elements are completeness, sensitivity, and consistency. Summary of completeness check is presented in Table 5. It clearly shows that this study does not provide a complete LCA as initially expected. Table 6 presents the result of consistency check for impact assessment of Vega production. With the available data, the study is consistent in in the methodology.

Table 5 - Summary of completeness check for environmental impact assessment for Vega production. Based on example set up from ISO 14044.

Unit process	Data available	Complete?	Action required
Chemical production	-	No	Retrieve information from manufacturer. Highly confidential, likely not possible to acquire.
Materials production	-	No	Retrieve information from manufacturer of materials used for packaging of chemicals and further how the packaging was produced.
Energy supply	X	No	Energy use was included in the emissions to air part of the total work. Supply of energy is mainly from onshore and partly from gas turbine. Generation of electricity sent from onshore is unknown.
Transport of chemicals	X	No	Find out where chemicals are produced. Transport from operator to offshore location is known.
Processing	X	Yes	
Waste management	X	No	Retrieve information on end of life for products from the waste management facility.
Transport of product	N/A	No	Expand scope
Refining	N/A	N/A	Expand scope
Packaging	N/A	N/A	Expand scope
Use	N/A	N/A	Expand scope
End of life	N/A	N/A	Expand scope

X: data entry available.
-: no data entry present.
N/A: not included in scope.

Table 6 - Result of consistency check for impact assessment of Vega production, after the ISO 14044 (2006).

Check	**Chemical products**	
Data source	NEMS Accounter	OK
Data accuracy	Moderate	OK
Data age	Updated	OK
Technology coverage	High for PW, moderate for residual discharge	OK
Time-related coverage	2010-2017	OK
Geographical coverage	Vega and Gjøa field, North Sea Region IV	OK

Table 7 - Variance in allocated weight of Biocide 1 by different allocation keys for sensitivity analysis. Allocation key used for calculating results for the study in bold text.

Allocated weight of Biocide 1 (kg)	**Unit and database for allocation key**
128,79	m^3 EEH
131,13	m^3 NPD
131,13	**m^3 NEMS Accounter**
144,02	Oil. eq. NPD
158,81	MJ NEMS Accounter
147,05	Oil. eq. EEH

Table 7 includes data used for sensitivity analysis performed for Biocide 1 to see how different production data changed the allocation keys and thereby the environmental burden weighted on Vega production. The sensitivity was calculated by the variance over the median, and found to be 13 %. Average weight was 137,99 kg. With the used allocation key in m^3 from NEMS Accounter, a 5 % difference weight was calculated in comparison to the average of all allocation keys.

7. ANALYSIS AND DISCUSSION

In establishing the contribution to environmental footprint modelling from sources resulting in discharge to sea, a large effort was put into developing a spreadsheet with a clear overview of allocated chemicals from the subsea installation and the host platform. Data for calculating contribution environmental risk could then further be retrieved from the inventory. To find the contribution to environmental risk posed by Vega measured by the EIF, results from new DREAM simulation was compared to previous simulations of the total discharge. Residual discharge not included as components in DREAM cannot be translated into one representative impact factor with the available data and software. As an estimation of the environmental footprint from Vega, discharge of all residual components was quantified.

7.1. Using outputs from the inventory

Originally having no discharge reported from Vega during operation, Figure 12 shows the actual discharge of Vega production chemicals only. Knowing that a list of chemicals is only used at Gjøa for Vega production it was already known that the difference would be significantly different from the original number of zero. Discharged amount is small compared to the usage. The largest contributor to discharge from Vega production is pH stabiliser (Figure 12). This chemical is classified as a green PLONOR chemical not posing a risk to the recipient. The hydrate inhibitor which ranges as the second largest contributor is also a PLONOR classified chemical. The scale inhibitor is the third largest contributor to usage.

Figure 13 shows the change in discharged amounts over the production phase. There is a drastic change in discharged amounts of Vega chemicals from 2015 which was when separate waste reports were first taken out providing a better understanding of what the waste from the MEG regeneration facility specifically contained. Looking back now it is known that the discharge was reported overestimated. Most of the chemicals ended up as waste and was transported onshore. Changing reported data is not done as the discharged amount has already been approved. As the 2013 numbers were not ran through DREAM, this did not affect the EIF results for this study. For further evaluation of the impact of discharge, Wintershall should take this overestimation under consideration.

One deliverable was data collection from the host platform Gjøa additionally. Total discharge of production and process chemicals was quantified from both installations in the developed Excel spreadsheet. Only an overview of the colour coded proportions of the discharge from Gjøa was included in this report as the focus was on Vega. Figure 14 shows the colour coding of all chemicals that were included in the study. Of Gjøa production chemicals, 94 % is classified as green while 6 % yellow. Vega production chemicals corresponding have larger contribution of yellow chemicals with 67 % and 33 % green. Vega total discharge includes the production chemicals and Gjøa chemicals that was allocated Vega, and this adding of Gjøa chemicals lowers the yellow portion slightly to 66 %. From this overview is it possible to draw the assumption that Vega has a larger contribution to the EIF than Gjøa. Vega well interventions discharge has a larger contribution of green chemicals with 79 %, but this is not included in the DREAM simulation as it does not follow the PW.

One of the goals of a LCA is to see how the footprint is dependent on the assessed process or product. With a correlation between discharged chemicals and produced volumes of hydrocarbons it would be possible to make an assumed prediction of the future discharge adding on the calculation of an environmental footprint. Attempting to connect the cumulative discharge per year to the functional unit of produced hydrocarbons could not be argued as successful. Correlation coefficients of total Vega discharge was 0,35 which does not correspond to any dependency on each other. Discharge amount of chemicals is not only dependant on the usage, but also the treatment before discharge. With a varying treatment process and reporting, the use and discharge of chemicals is not proportional either. Use of chemicals are more dependent on the production conditions, amount of produced water and field age. The use of chemicals and production gives a better correlation of 0,82 even though it is not significant enough to state that the amount of chemicals used is depending on the production. This makes it difficult to relate the marine discharge to functional unit which is what the LCA fundamentally builds on.

The hazardous waste from the MEG regeneration facility is most likely burned. Further interpretation of produced waste is not achievable as no other information rather than that all has an efficiency of energy recovery of 100 %.

7.2. Vega contribution to environmental risk, today and in the future

New DREAM simulations generated results that were compared to an impact assessment for original LCAs. The 2013 simulation was left out of further analysis as the results were not comparable to the previous simulations. Reasons for that outcome are several.

Numbers in the database may have been updated giving new discharge amounts for some or several chemicals. The HOCNF forms for chemicals may also have been updated from 2013 until today resulting in different toxicity measures and input data in DREAM. To be able to generate comparable results, HOCNF data for original input list would be necessary. Another option would have been to recalculate the EIF for both total discharge and Vega discharge with current data in NEMS Accounter. Unfortunately, the time was not sufficient for a comparative result of 2013 in this thesis work. For the results from 2016 it was however possible to say something about the Vega contribution.

Preparing data for the Vega DREAM simulation, concentrations of chemical additives calculated for Vega were compared to those from the original report. Several chemicals are only used for Vega hence the concentrations for the same chemical for the same year should be identical. Instead, all concentrations were deviating with a difference of 10^6. This discovery resulted in the need to run an updated simulation of the total data. The 2016 EIF value for total discharge from Vega and Gjøa were recalculated from 2 to 8. Updated value is still below the limit of 10 meaning there is not a difference in reporting criteria or change in chemicals other than on the reputational line. Had the initial value been larger however, an increased risk (>10) might have been posed to the environment unnoticed for numerous of years.

After receiving the updated EIF calculation of the total discharge, the simulation of Vega contribution could be run. The assumption that Vega had a higher contribution to the EIF than Gjøa was correct. Vega proved to account for 7 out of 8 of the EIF value. Only the output of the pie chart was included in the report as it presents the results needed for evaluating the Vega contribution. As the calculated EIF is lower than the threshold value

of 10, it is not of high importance to reduce the risk. Trying to lower the environmental footprint, it is still essential to know where a change has the most positive effect. The corrosion inhibitor 1 is the largest contributor to the EIF with component 5 of 77 % and component 4 of 10 %. This chemical is added only for the Vega production and is a chemical that Wintershall can evaluate to replace by a less hazardous one. Biocide 2 and 2 are injected by Neptune and are thereby not possible to affect primarily by Wintershall. Again, with such a low EIF it is not likely to prioritise their substitution.

The quality of the comparison basis is debateable. Although new reporting requirements from 2013 to 2016 resulted in a different and improved understanding of input data, the concentration of each component was not included in the available report. Every chemical is composed of several components that each has an assigned range of percentage composition given in the HOCNF. Exact contribution in that range is although not given. DREAM is a sensitive model meaning with different assessors assigning different percentage composition to some components, the resulting EIF value might change. With the original report available, it was possible to back calculate the percentage composition of each component to be able to use the same assignment for the Vega simulation.

Allocation of Gjøa chemicals to Vega production could also have affected the Vega contribution to the total EIF. Basing the allocation on production volumes was decided as best assumption for correct burden to each installation with the available information. The need for chemicals for a production stream can also be dependent on the physical and chemical characteristics of the wellstream. Vega has a lighter composition producing gas and condensate, compared to Gjøa which is producing more oil. This could result in

differences in requirement of different chemicals. Evaluating the amount of chemicals allocated to Vega production depending on the different allocation options, a discharge weight variation of 5 % from the average of all possibilities was found for allocated chemical with largest contribution, Biocide 1. This corresponded to an allocated weight varying from 128,79 to 147,05. To find how sensitive the calculated EIF for Vega is related to the allocation key, another simulation is required.

For the predicted EIF in the case study for 2021, the calculation resulted in EIF = 43 which is significantly higher than what it was in 2016 and assumed to still be today. Such a high EIF is way above 10 meaning that if it will be the case, a new EIF will have to be calculated every year. The large difference even with fewer chemicals in the injected mixture, was the background on the decision to run a revised simulation where the PW volume was doubled hence halving the discharge concentrations. The revised calculation resulted in EIF = 44. It is evident that the sensitivity in the model lies more in the discharge amount rather than the discharge concentration. A footprint should also be dependent on the actual amount of discharge.

The largest contributor to the EIF is still the corrosion inhibitor 1 with component 5 (81 %) and component 4 (11 %). The reason for the high EIF is subsequently due to the large amount of discharged corrosion inhibitor which commonly is a hazardous chemical (Miljødirektoratet, 2016). Calculation of input value was dependent on the PW volume. The reason why Wintershall has investigated the possibilities of change in the Vega production chemicals is due to the expected volumes of PW which is exceeding the capability of the current system. In this future scenario, it is likely to be of much higher interest to find a replacing chemical with lower toxicity. From the available estimate of

PW, it provides the best estimate of usage of corrosion inhibitor. The discharge factor was taken from the HOCNF which provides a conservative measure, but without further knowledge of the actual discharge factor it again provides the best estimate.

Uncertainties are affecting all aspects of this study and the largest are related to predicted values given in HOCNF, applied discharge factor of production chemicals, weighted concentrations of natural components, and more. The two latest analysis, both from 2017, were used as assumption of concentrations for natural components. The actual concentration in the year of interest will most likely be different. Regarding expected concentrations of production chemicals, there are large uncertainties too. Dosage volume are known. These are based on volumes of PW that is estimated but again with large uncertainties. This is due to the change in water volumes as well as possible depletion of some components in the reservoir. In 2021 Vega PW will most likely be led through the water cleaning facility currently only used for Gjøa production. It is feasible that different volumes will be discharged than what is calculated for discharged chemicals here.

7.3. Choice of methodology

Reaching a suitable methodology has been one of the most challenging aspects working on this thesis. Calculation of environmental footprint is new on the agenda within Wintershall. During the start phase of this work, a considerable amount of time was spent to find a methodology that would cover the goal of calculating the environmental footprint from Vega. The term environmental footprint originates from LCA. Conducting a LCA with limited time and data, and without commercial software is not a common approach. Narrowing down the total work by splitting it to emissions to air and discharge

to sea was the first step to a more defined scope. Most LCAs include all environmental impacts that can be related to the studied product. However, investigating discharge to sea it was decided that focusing only on the impact category of marine ecotoxicity defined the scope to work in further. By the LCA approach, all discharged components were to be translated into equivalents of a same factor. Previous studies have used DCB equivalent as the impact factor when assessing marine ecotoxicity. Possibilities for calculations of DCB equivalent were investigated thoroughly but found for only natural components and not specifically for the chemical additives.

Consulting with Wintershall it was agreed that translating all components of the Vega discharge to DCB equivalent would not give a valuable result. Even if all constituents of the discharge were translated to DCB equivalent, it would add no value to the results at the time. The EIF on the other hand would give interpretable results, comparable to all other fields on the NCS. Guinée et al. (2002) present in their guide that the category indicator equals PEC/PNEC. Calculated EIF values are based on the same approach where DREAM calculates the PECs. Based on this knowledge it could be justified to implement EIF calculations for the step of impact assessment. If the PEC could be found from field measurements, it would have been an ideal approach. Due to the rapid dilution rate of a discharge this rarely provide good results (Sanni et al., 2017), and field work was never considered to be implemented in this study.

The methodology was then combining ERA and environmental impact assessment, which Hauschild et al. (2015) have described as two similar methodologies that also have important differences. Both LCA and ERA aim to evaluate the potential hazardous impact on the environments based on available data and assumptions. Data used for the

ERA always use numbers representing the worst case scenario while for the LCA, most reasonable estimates are used. The ERA is mainly conducted for regulatory means for a given area. The LCA is most often calculated under steady-state conditions and focus on the global aspect of impacts rather than local (Guinée et al., 2002). The ISO 14040 (2006) also state that the LCA is different from risk assessments and environmental impact assessments, but that the results of these other methods can be implemented in the LCA. The DREAM model is however a conservative model using worst case scenario input. Calculated ecological risk therefore have a potential to be overly conservative (Neff et al., 2011). Johnsen and Frost (2011) recommends the results only to be used as a guideline and not a descriptive tool for measurement of the ecological status.

Having this in mind, a full LCA was not to possible be accomplished with this work. Still aiming towards an environmental footprint, the holistic and comprehensiveness of the LCA approach was necessary. Finkbeiner (2016) describes life cycle thinking as a good starting point for an organisation initiating sustainability considerations. Following life cycle thinking became the main guideline for the methodology aiming to include as many aspects from the LCA as possible and supplement with DREAM for the impact assessment for a better understanding of the results with the current knowledge.

7.4. Towards a total environmental footprint

Wintershall wanted to calculate an environmental footprint without having defined what it is or should include. Parts of the work was therefore to define what it really is. Learning that environmental footprint originates from LCA, a total footprint will require a complete LCA including all impact categories that that can be linked to all outputs from

the total inventory. To accomplish this, remaining life cycle phases of refining, use, and disposal of the processed hydrocarbons would also be included. With early split in total workload the deliverable was shifted to only focusing on environmental footprint related to discharges to sea, further scoped to the production phase.

A completeness check of the study adapted from the ISO 14044 (2006) was performed based on the full life cycle of all sources that could be related to discharge to sea. Through this check it is evident that several inclusions are to be made for a more complete assessment. Unit processes from Table 5, listed as not included in this study, relates to the origin or production of inputs to the process system (e.g. process of producing chemicals and materials from raw materials). Most of the data necessary for implementation of this to a LCA is not available and/or highly time consuming difficult to retrieve. Numerous separate studies would have had to be performed by all manufacturers and operators of mobile installations for a very large-scale assessment. In relations to the transportation of chemicals by vessels, these could be from distant locations. It was assumed that the discharges along the travel route is very small and quickly diluted making it close to impossible to measure the output. Accidents related to these transportations are as mentioned reported under marine operations, but could potentially be further investigated, although most likely not providing a large difference.

It is necessary to translate all discharge components to impact factors to be able to move to the next step of LCA with an impact assessment of the complete inventory analysis. DREAM provided a good indication of which components in the PW are contributing to the environmental risk. The risk gives the best indication of what the actual effect is, which is also the goal of the impact assessment in an LCA. The interpretation can be

done with a total environmental footprint as comparing different outputs will also enhance where along the process an improvement should be implemented first. How the waste is managed, and what sort of emissions or waste products is produced after treatment could be a separate study. Same goes for the phases after the produced hydrocarbons leaves the Gjøa platform in export pipelines. Use and end of life for condensate, oil, and gas varies over a wide spectre. Separate assessments would have to be done before being combined for a total environmental footprint.

Shifting results of risk assessments with the EIF to impact or effect results is interesting in terms of being able to state what the actual footprint of a discharge to sea is. Linking DREAM with biomarkers with biomarker bridges have potential to predict biomarker responses translating the risk picture of EIF to a PAF picture. This would require a separate study but the risk pictures from this study could be used.

Input to the DREAM model does not consider potential, and likely, reaction of chemical mixtures before or after discharge. Rather it assumes that the discharge is composed of the same chemistry as what was injected. This is mainly due to lack in research on how the various chemicals respond to the changes in pressure and temperature, as being exposed to other chemicals and the equipment. The applied method for measurement of WET on the Vega field today is the field environmental monitoring. Monitoring has so far concluded that surrounding species and benthic fauna remains unaffected since production start in 2010. Progress in the WET modelling may reduce the necessity of field work in the future. A model should still only be supplementary for improvement and understanding of the modelling as no human made model can ever truly understand the extensive complexity of nature.

8. CONCLUSION

The aim of this study was to develop a model to calculate the total environmental footprint. Soon after dividing the work into emissions to air and discharge to sea and conducting research of what an environmental footprint should include, it was decided that the total footprint was not accomplishable within the given timeframe. The results from this approach rather provides a preliminary study of the total environmental footprint by the impact of discharge to sea during the production phase. Following the LCA which is the one method linked to calculation of footprints, provided an approach focusing on a broader aspect compared to the already established method of DREAM with the EIF. Guinée et. al. (2002) mention there is a limitation in choice of methodology that is applicable to nearly all steps of the LCA. And further that the holistic approach leads to several technical assumptions and selected value choices. Assumptions and value choices made have been described to enhance the transparency of the results. Deciding to only use data from one database made a more consistent base for reaching the results. No other subsea installations have reported their discharge as they are all connected to a surface installation, either a platform or connected to shore (except for Snøhvit that is connected to shore). This makes the results of this thesis unique. EIF values does not differentiate between subsea or surface installations. Resulting EIF values from this study can therefore be used for comparison with all other production installations on the NSC.

Despite the limitations and uncertainties, this study provides the best estimate to the environmental footprint of discharge from Vega production. The methodology and results from this thesis provides a good baseline to quantifying the total environmental footprint of Vega. The transparency of the work makes it possible to use the set up for modelling

of other subsea fields. The adapted Maslow's pyramid by Finkbeiner (2016) can additionally inspire to further work towards a sustainable industry.

Recommendations for future work:

- Expand scope to include more phases of the gas production life cycle for a more holistic picture of the environmental impact of Vega subsea installation.
- Further investigation of how to translate all components in a PW discharge to the same impact factor.
- More work should be done on understanding the exact amount of a chemical that enters the sea to be able to calculate a more correct footprint.
- Being the first approach for calculating a footprint, it is recommended to use the results as a baseline for future work.
- Further assessment investigating use of WET for a more realistic understanding of the environmental effects.

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10. APPENDIXES

Appendix 1

The NEA's table for classifying and reporting chemicals (NOROG miljørapport 2016):

Discharge	**Category[1]**	**NEA colour category**
Substances on Ospar's PLONOR list	201	Green
Substances covered by Reach annex IV[2]	204	Green
Certain substances covered by Reach Annex V[3]	205	Green
Substances with no test data	0	Black
Substances thought to be, or which are, hazardous to genes or reproduction[4]	1.1	Black
List of prioritised substances in result objective 1 (priority list)	2	Black
Biodegradability < 20% and log $P_{ow} \geq 5$[5,4]	3	Black
Biodegradability < 20% and toxicity EC_{50} or $LC_{50} \leq 10$ mg/l[4]	4	Black
Two out of three categories: Biodegradability < 60%, log $P_{ow} \geq 3$, EC_{50} or $LC_{50} \leq 10$ mg/l	6	Red
Inorganic and EC_{50} or $LC_{50} \leq 1$ mg/l	7	Red
Biodegradability < 20%[4]	8	Red
Substances with biodegradability > 60%	100	Yellow
Substances with biodegradability 20-60%		
Sub-category 1: expected to biodegrade fully	100	Yellow
Sub-category 2: expected to biodegrade to environmentally non-hazardous substances	101	Yellow
Sub-category 3: expected to biodegrade to substances which could be environmentally hazardous	103	Yellow

[1] A description of the category is provided in the flow diagram.

[2] Removed from the black category in the activities regulation.

[3] Substances hazardous to genes or reproduction are understood to mean mutagen categories (Mut) 1 and 2 and reproduction categories (Rep) 1 and 2 of hazardous chemicals or self-classification.

[4] Data for degradability and bioaccumulation must accord with approved tests for offshore chemicals.

[5] Removed from red category in the activities regulations.

[6]Commission regulation 987/2008. The NEA must assess whether the substance is covered by annex V.

Green: Chemicals considered to have no or very limited environmental impact. Can be discharged without special conditions.

Yellow: Chemicals in use, but not covered by any of the other categories

Red: Chemicals which must be given priority for substitution, but which can be discharged with government permission.

Black: Chemicals which the government can permit to be discharged in special circumstance – where there is crucial for safety, for instance.

Appendix 2

Input data for the DREAM simulations. General field data.

Field information for the discharges considered					
		2013	**2016**	**2021**	**2021 revised**
Field	Vega (Gjøa)				
Region	North Sea				
Position	61°19'56.51" N 3°53'48.55" E				
Release depth (m)	6				
Release rate m3/year	Vega	18205,8	27963	106303	
Relase rate m3/day	Vega	50	77	291,2	
Release rate m3/year	Gjøa (tot)	193824	767966	421140	842280
Relase rate m3/day	Gjøa (tot)	530	2104	1154	2307,616438
Current- and wind files to be used in EIF calculation					
Region	**Current file**	**Wind file**			
The North Sea	May90.dir	Gullfaks.wnd			

Natural components for 2013, 2016 and 2021. Revised 2021 data performed at IRIS.

Input concentrations and corresponding PNEC values

2013	PW total volume	193824
2016	PW total volume	767966
2021	PW total volume	421140

Field: Vega Components	OSPAR PNEC µg/l (ppb)	2013 Concentrations* Mg/l	2016 Concentrations* Mg/l	2021 Concentrations** Mg/l
Benzene	8	0,93	0,67	0,83
Toluene	7,4	0,95	0,62	0,81
Ethylbenzene	10	0,057	0,032	0,043
Xylene	8	0,37	0,232	0,326
Napthalene	2	0,5483	0,1388	0,1130
Acenaphthene	0,38	0,00035	0,00011	0,000082
Acenaphtylene	0,13	0,000095	0,00003	0,000023
Fluorene	0,25	0,00367	0,00098	0,00062
Anthracene	0,1	0,0000051	0,00000084	0,00000065
Phenanthrene_incl_substitutes	1,3	0,0022	0,000615	0,00046
Dibenzothiophene_incl_substitutes	0,1	0,000671	0,000069	0,00021
Fluoranthene	0,01	0,000027	0,0000010	0,0000036
Pyrene	0,023	0,000018	0,0000013	0,0000059
Benz(a)anthracene	0,0012	0,000003	0,00000018	0,0000015
Chrysene	0,007	0,000010	0,0000002	0,000005
Dibenzo(a-h)anthracene	0,00014	0,0000012	0,00000018	0,00000025
Benzo(g-h-i)perylene	0,00082	0,0000075	0,0000002	0,00000078
Benzo(a)pyrene	0,022	0,0000032	0,00000018	0,00000043
Benzo(k)fluoranthene	0,017	0,0000025	0,00000018	0,00000025
Indeno(1-2-3-cd)pyrene	0,00027	0,0000020	0,00000036	0,00000050
Benzo(b)fluoranthene	0,017	0,000012	0,000000	0,0000036
Phenol(C0-C3-alkyl-phenols)	7,7	10,6952	3,6197	4,3775
Butylphenol(C4-alkyl-phenols)	0,64	0,1314	0,0446	0,0462
Pentylphenol(C5-alkyl-phenols)	0,2	0,0240	0,00770	0,00716
Octylphenol(C6-C8-alkyl-phenols)	0,01	0,0005	0,000069	0,000059
Nonylphenol(C9-alkyl-phenols)	0,3	0,000008	0,000002	0,000004
Dispersed-oil	70,5	1,684637	0,2992459	0,3020375
Arsenic	0,6	0,000047	0,000009	0,0000248
Cadmium	0,21	0,0000070	0,0000	0,0000
Chromium	0,6	0,002184	0,000009	0,000025
Copper	2,6	0,000083	0,0000091	0,0000037
Nickel	8,6	0,006750	0,00003	0,000083
Mercury	0,048	0,000042	0,000026	0,000069
Lead	1,3	0,0000094	0,0000	0,00020
Zinc	3,4	0,010804	0,000073	0,000022

*For comparison with already calculated Gjøa EIF

** Predictive concentrations based on latest PW analysis taken from Vega, 24.02.2017 and 29.11.2017

Chemical additives 2013.

HOCNOF information and concentration for added chemicals at Vega							
% composition	Chemical name	Component	Chemical Total discharge kg	Concentration (mg/l)	Bioaccum. LogPow*	Biodegradation % 28dg**	PNEC ppb, EC50 / LC50 / 1000**
2013							
	Cleaning agent		8956,8	46,21			
	H2S scavenger		**8754,80**	**45,17**			
35 %		Component 1	3064,18	15,81	2,7	102,2	2
65 %		water, distilled, c	5690,62	29,36			
	Corrosion inhibitor I		**9996**	51,57			
45 %		Component 1	4498,2	23,21	1,3	71	125
0,5 %		Component 2	49,98	0,26	0	28	16
15 %		Component 3	1499,4	7,74			
5 %		Component 4	499,8	2,58	0,54	69	0,045
30 %		Component 5	2998,8	15,47	0,75	71	0,046
0,5 %		Component 6	49,98	0,26	0	74	500
0,5 %		Component 7	49,98	0,26	0,3	81	316
0,75 %		Component 8	74,97	0,39			
2,75 %		water, distilled, c	274,89	1,42			
	Hydrate inhibitor		**40363,86**	208,25	PLONOR	PLONOR	PLONOR
	Scale inhibitor II		**24296,73**	125,35			
41 %		Component 1	9961,65951	51,40		35	545
28 %		meg	6803,08454	35,10		81	
		Component 3		0,00			
		Water		0,00			
	pH stabiliser		**203224**	1048,50			
30 %		Component 1	60967,2	314,55			
70 %		water, distilled, c	142256,8	733,95			
	Antifoam		**31,75**	**0,16**			
0,1-0,3		Component 1		0,00	1,6	60,2	1100
0,6-0,6		Component 2		0,00	5,06	72	10000
0,1-0,3		Component 3		0,00	1,09	39	18,64
	Demulsifier		**63,16**	**0,33**			
0 %		Component 1	0,01	0,00003			11
0 %		Component 2	0,20	0,00104	1,28	52	28
93 %		Component 3	59,03	0,30454			1000
1 %		Component 4	0,41	0,00209	2,65	29	15
3 %		Component 5	1,80	0,00927	0,1	22	42
	Gas treatment		**1247,14**	**6,43**			
100 %		Component 1	1247,14	6,43	0	23	1000

Chemical additives 2016.

% composition	Chemical name	Component	Chemical Total discharge kg	Concentration (mg/l)	Bioaccum. LogPow*	Biodegradation % 28dg**	PNEC ppb, EC50 / LC50 / 1000**	Used (kg)
2016								
			22513,20	**29,32**				**22513**
	Wax inhibitor		**549,91**	**0,72**				**12830**
100 %		Component 1	549,89	0,716039	0,0002	41	1000	
0 %		Component 2	0,01	0,000019	4,77	70	222	
	Corrosion inhibitor I		**640,31**	**0,83**				**25610**
45 %		Component 1	288,1373	0,38	1,3	71	125	
0,5 %		Component 2	3,2015	0,00	0	28	16	
15 %		Component 3	96,0458	0,13				
5 %		Component 4	32,0153	0,04	0,54	69	0,045	
30 %		Component 5	192,0915	0,25	0,75	71	0,046	
0,5 %		Component 6	3,2015	0,00	0	74	500	
0,5 %		Component 7	3,2015	0,00	0,3	81	316	
0,75 %		Component 8	4,8023	0,01				
2,75 %		water, distilled, c	17,6084	0,02				
	Hydrate inhibitor		**26192,90**	34,11	PLONOR	PLONOR	PLONOR	**2619290**
	Scale inhibitor II		**383,45**	**0,50**				**15340**
41 %		Component 1	157,21368	0,2047144		35	545	
28 %		Meg	107,36544	0,139805		81		
		Component 3		0,00				
		Water		0,00				
	Biocide I		**131,13**	**0,170755**				
21 %		Component 1		0,035947	-0,33	74,3	0,11	
	Biocide II		**236,80**					
20 %		Component 1		0,061668	<0	57	0,24	
	Demulsifier		**1514,81**	**1,97**				**4266**
0 %		Component 1	0,14	0,000179			11	
0 %		Component 2	4,85	0,006319	1,28	52	28	
93 %		Component 3	1415,66	1,843385			1000	
1 %		Component 4	9,73	0,012673	2,65	29	15	
3 %		Component 5	43,09	0,056103	0,1	22	42	
	Gas treatment		**15422,92**	**20,08**				**18933,47**
100 %		Component 1	15422,92	20,08	0	23	1000	

Chemical additives 2021 and 2021 revised.

% composition	Chemical name	Component	Chemical Total discharge kg	Concentration (mg/l)	Bioaccum. LogPow*	Biodegradation % 28dg**	PNEC ppb, EC50 / LC50 / 1000**	Used (kg)
2021								
	Corrosion inhibitor I		**3649,05**	**8,66**				**24327,00**
45 %		Component 1	1642,0725	3,90	1,3	71	125	
0,5 %		Component 2	18,24525	0,04	0	28	16	
15 %		Component 3	547,3575	1,30				
5 %		Component 4	182,4525	0,43	0,54	69	0,045	
30 %		Component 5	1094,715	2,60	0,75	71	0,046	
0,5 %		Component 6	18,24525	0,04	0	74	500	
0,5 %		Component 7	18,24525	0,04	0,3	81	316	
0,75 %		Component 8	27,367875	0,06				
2,75 %		water, distilled, c	100,348875	0,24				
	KHI		**212606,00**	**504,83**				**2126060,00**
30 %		Component 1	63781,80	151,4503491	0	65	27,96	
70 %		Component 2	148824,20	353,3841478	0	67	2865,33	
	Wax inhibitor		**808,85**					**18876,90**
100 %		Component 1	808,82	1,920558	0,0002	41	1000	
0 %		Component 2	0,02	0,000051	4,77	70	222	
	Gas treatment		**17324,62**					**21321,646**
100 %		Component 1		41,14	0	23	1000	
	Biocide II		**74,03**					
20 %		Component 1	14,805531	0,035155841	<0	57	0,24	
	Biocide III		**607,03**					
20 %		Component 1	121,405354	0,288278	<0	57	0,24	
	2021 revised with double water volume							
	Corrosion inhibitor I		**3649,05**	**4,33**				**24327,00**
45 %		Component 1	1642,0725	1,95	1,3	71	125	
0,5 %		Component 2	18,24525	0,02	0	28	16	
15 %		Component 3	547,3575	0,65				
5 %		Component 4	182,4525	0,22	0,54	69	0,045	
30 %		Component 5	1094,715	1,30	0,75	71	0,046	
0,5 %		Component 6	18,24525	0,02	0	74	500	
0,5 %		Component 7	18,24525	0,02	0,3	81	316	
0,75 %		Component 8	27,367875	0,03				
2,75 %		water, distilled, c	100,348875	0,12				
	KHI		**212606,00**	**252,42**				**2126060,00**
30 %		Component 1	63781,80	75,72517453	0	65	27,96	
70 %		Component 2	148824,20	176,6920739	0	67	2865,33	
	Wax inhibitor		**808,85**					**18876,90**
100 %		Component 1	808,82	0,960279	0,0002	41	1000	
0 %		Component 2	0,02	0,000025	4,77	70	222	
	Gas treatment		**17324,62**					**21321,646**
100 %		Component 1		20,57	0	23	1000	
	Biocide II		**74,03**					
20 %		Component 1	14,805531	0,017577921	<0	57	0,24	
	Biocide III		**607,03**					
20 %		Component 1	121,405354	0,144139	<0	57	0,24	

Appendix 3

Complete calculations for concentration input values for the case study set to year 2021.

For all equations:

m = mass,

ρ = density,

V = volume (m^3 or l),

wt% = weight percentage

Kinetic hydrate inhibitor (KHI):

Weight percent of injected KHI was set to be 2% on the water side after knowing it can vary from 2-4 %, see section 4. Case study.

$$wt\% = \frac{m\ (kg)_{KHI}}{m\ (kg)_{Water} \cdot m\ (kg)_{KHI}} = 0.02$$

Where:

ρ_{KHI} = 1.0 (1000 kg/m^3), and

ρ_{water} = 1000 kg/m^3.

Used amount of KHI was found based on properties of the chemical, known planned dosage compared to the water phase, and estimated Vega PW volume.

$$V_{KHI} = V_{PW} * 0.02$$

$$V_{KHI} = 106\ 303\ m^3 * 0.02 = 2\ 126.06\ m^3$$

$$m_{KHI} = V_{KHI} * \rho_{KHI} = 1000\ \frac{kg}{m^3} * 2\ 126.06\ m^3 = \ 2\ 126\ 060\ kg$$

The discharge concentration was based on the total estimated PW volume from both Vega and Gjøa in 2021 = 421 140 000 l. Following EIF approach of the worst-case scenario, the results should be a good conservative estimation. Discharge factor for KHI = 10% on product level, giving estimated concentration in discharge;

$$m_{KHI,disch} = 2\,126\,060\ kg * 0.10 = 212\,606\ kg$$

$$C_{KHI} = \frac{m(mg)}{V(l)}$$

$$C_{KHI} = \frac{212\,606\ kg * 1\,000\,000\ \frac{mg}{kg}}{421\,140\,000\ l} = 504.83\ mg/l$$

Corrosion inhibitor:

Corrosion inhibitor was assumed to be injected at a rate of 225 ppmV. HOCNF report gives that 15% of used chemical is discharged.

ρ_{CI} = 1020 kg/m^3.

$$V_{CI} = V_{PW} * 225ppm$$

$$V_{CI} = 106\,000\ m^3 * 225ppm = 23.85\ m^3$$

$$m_{CI} = \rho_{CI} * V_{CI} = 1020\ \frac{kg}{m^3} * 23.85m^3 = 24\,327\ kg$$

$$m_{CI.disch} = 0.15 * m_{CI} = 0.15 * 24\,237\ kg = 3\,649.05\ kg$$

$$C_{CI} = \frac{3\,649.05\ kg * 1\,000\,000\ \frac{mg}{kg}}{421\,140\,000\ l} = 8.66\ mg/l$$

Appendix 4

Inventory of all chemicals used and discharged from Vega and Gjøa from production start in 2010 until latest updated data in 2017. No trade names of chemicals are included due to confidentiality.

Description Function group	Storage tank		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Cumulative	Colour code	Contribution EIF (Time avg) 2016
VEGA PRODUCTION																	
Continous injection to templates																	
Scale inhibitor	42TB059	Discharged (kg)	1290,45	31165,41	31862,44	24296,73	30589,81	13,33	9,59	1,69					119229,45		0
		Used (kg)	1290,45	32805,70	33539,41	25575,49	32199,80	21323,15	15337,92	6759,80					168831,72		
Hydrate inhibitor	67TB306/67TB352/	Discharged (kg)	1518,00	6925,38	497933,39	40363,86	76396,10	21453,41	26192,90	17863,65					688646,69		0,0001
		Used (kg)	151800,00	692538,00	774873,00	789800,00	1513270,00	2145341,00	2619289,68	1786365,00					10473276,68		
Corrosion inhibitor	42TB052	Discharged (kg)	966,00	3105,48	7875,00	9996,00	2129,40	15,47	16,01	5,23					24108,58		6,452
		Used (kg)	966,00	7763,70	19687,50	24990,00	26670,00	24748,50	25612,20	20910,00					151347,90		
pH stabiliser	42TB054	Discharged (kg)	1596,00	120897,00	172873,40	203224,00	211470,00	208756,80	194419,75	129482,50					1242719,45		-
		Used (kg)	1596,00	120897,00	172873,40	203224,00	211470,00	208756,80	194419,75	129482,50					1242719,45		
Vega step 1 and 2 separator																	
H2S scavenger I	42TB056	Discharged (kg)		14557,40	12826,80	8754,80	8144,00	382,21							44665,21		-
		Used (kg)		14557,40	12826,80	8754,80	8144,00	610,80							44893,80		
HSS scavenger II	42TB056	Discharged (kg)	816,00	3488,40						453,96					4758,36		-
		Used (kg)	816,00	3488,40						907,91					5212,31		
Demulsifier	42TB053	Discharged (kg)						8,88	35,54						44,42		See allocated Vega
		Used (kg)						84,00	336,00						420,00		
Chemicals added for a limited time																	
Wax inhibitor	42TB055	Discharged (kg)	0,00	0,00	0,00	0,00	0,00	808,85	549,91	777,96					2136,71		0
		Used (kg)	9078,00	326783,97	64631,80	27323,00	20559,00	18876,90	12833,80	18156,00					498242,47		
Cleaning agent (MEG system)	38TA005	Discharged (kg)	1492,8	11046,72	3358,8	8956,8		873,6	22513,2	18096					66337,92		See MEG
		Used (kg)	1492,8	11046,72	3358,8	8956,8		873,6	22513,2	18096					66337,92		
Hydraulic liquid (Vega utility)	?	Discharged (kg)		0	0	0	0								0,00		-
	Bård Nordheim	Used (kg)		1664	1857,6	1664	1664								6849,60		
GJØA PRODUCTION																	
Production chemicals																	
Wax inhibitor	42TB005	Discharged (kg)						270,00							270,00		-
		Used (kg)						270,00							270,00		
Wax inhibitor		Discharged (kg)						739,01							739,01		-
		Used (kg)						1738,5							1738,50		
Scale inhibitor B	42TB002	Discharged (kg)					54162,33	61645,58	62258,20						178066,11		
		Used (kg)					54162,33	69864,99	63758,40						187785,72		
Scale inhibitor		Discharged (kg)		3613,05	12204,08	12961,1	18019,37								46797,60		-
		Used (kg)		3613,05	12204,08	12961,1	18019,37								46797,60		
Scale inhibitor C	42TB003	Discharged (kg)							14372,60	97891,43					112264,0343		
		Used (kg)							15679,20	98745,60					114424,8		
Flocculant	42TB007	Discharged (kg)						5626,80	7943,72	8458,59					22029,11		0
		Used (kg)						6377,04	9002,88	9586,40					24966,32		
Scale inhibitor A	42TB001	Discharged (kg)	333300	2060454	1453826	812130	1039830	1176010,00	660463,10	759288,50					8295301,60		
		Used (kg)	333300	2064304	1453826	812130	1039830	1176010,00	695224,32	759288,50					8333912,82		
Process chemicals - Common with Vega process																	
Antifoam	42TB004	Discharged (kg)		189,00	936,60	113,40		10,79							1249,79		-
		Used (kg)		378,00	1873,20	226,80		336,00							2814,00		
Demulsifier	42TB006	Discharged (kg)		38,59	62,93	225,61	486,62	9176,45	4976,32						14966,52		See allocated Gjøa
		Used (kg)		385,94	629,25	2265,30	4866,20	12417,10	6485,07						27048,86		
Biocide		Discharged (kg)					1130	1243,00	452,00						2825,00		See allocated Gjøa
		Used (kg)					1130	1243,00	452,00						2825,00		
Biocide	42TB014	Discharged (kg)							816,20	282,50					1098,70		See allocated Gjøa
		Used (kg)							816,20	282,50					1098,70		
Biocide		Discharged (kg)								2316,50					2316,50		-
		Used (kg)								2316,50					2316,50		
Gas treatment	68TB001	Discharged (kg)	0,00	7051,50	6440,06	4455,10	3841,88	55495,71	53167,31	66121,76					196573,32		See allocated Gjøa
		Used (kg)	10125,00	141030,00	128801,25	89100,00	76837,50	69369,64	66459,14	82652,20					664374,73		
Oxygen scavenger	38TA003	Discharged (kg)													0,00		-
		Used (kg)													0,00		
Export chemicals - Common with Vega production																	
Corrosion inhibitor	42TB015	Discharged (kg)	0,00	0,00	0,00	0,00	0,00	0,00	0,00						0,00		-
		Used (kg)	3769,80	59461,90	71801,30	65302,00	48101,00	42549,30	39253,30						330238,60		
Wax inhibitor		Discharged (kg)			0,00	0,00									0,00		-
		Used (kg)			285,00	2090,00									2375,00		

Inventory of allocated chemicals.

Description	Function group	Storage tank		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Cumulative	Colour code	Contribution EIF (Time avg) 2016	Ak
WEIGHTED CHEMICALS WITH ALLOCATION KEYS																			
Common chemicals weighted for Vega production contribution																			
Antifoam		42TB004	Discharged (kg)	0,00	56,11	245,12	31,75	0,00	3,32	0,00	0,00					336,29		-	Total
			Used (kg)	0,00	112,21	490,23	63,50	0,00	103,23	0,00	0,00					769,17			production
Demulsifier		42TB006	Discharged (kg)	0,00	11,46	16,47	63,16	159,12	2828,17	1479,27	0,00					4557,65		0,002	Total
			Used (kg)	0,00	114,57	164,68	634,20	1591,20	3898,91	2217,45	0,00					8621,01			production
Biocide 1			Discharged (kg)	0,00	0,00	0,00	0,00	369,50	381,89	131,13	0,00					882,52		0,239	Total
			Used (kg)	0,00	0,00	0,00	0,00	369,50	381,89	131,13	0,00					882,52			production
Biocide 2		42TB014	Discharged (kg)	0,00	0,00	0,00	0,00	0,00	0,00	236,80	74,03					310,82		0,183	Total
			Used (kg)	0,00	0,00	0,00	0,00	0,00	0,00	236,80	74,03					310,82			production
Biocide			Discharged (kg)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	607,03					607,03		-	Total
			Used (kg)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	607,03					607,03			production
Gas treatment		68TB001	Discharged (kg)	0,00	2093,75	1685,57	1247,14	1256,07	17047,26	15422,92	17324,62					56077,32		0,01	Gas
			Used (kg)	1897,10	41874,98	33711,35	24942,18	25121,47	213309,08	19278,65	21635,77					186790,57			
Corrosion inhibitor		42TB015	Discharged (kg)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00					0,00		-	Oil
			Used (kg)	471,13	13681,94	16631,39	21925,32	21093,29	18725,42	16190,84	0,00					108919,34			
Wax inhibitor			Discharged (kg)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00					0,00		-	
			Used (kg)	0,00	0,00	66,01	701,72	0,00	0,00	0,00	0,00					767,74			
Common chemicals weighted for Gjøa production contribution																			
Antifoam		42TB004	Discharged (kg)	0,00	132,89	691,48	81,65	0,00	7,48	0,00	0,00					913,51		-	Total
			Used (kg)	0,00	265,79	1382,97	163,30	0,00	232,77	0,00	0,00					2044,83			production
Demulsifier		42TB006	Discharged (kg)	0,00	27,14	46,46	162,45	327,50	6348,28	3497,06	0,00					10408,88		0,002	Total
			Used (kg)	0,00	271,37	464,57	1631,10	3275,00	8518,19	4287,62	0,00					18427,85			production
Biocide 1			Discharged (kg)	0,00	0,00	0,00	0,00	760,50	861,11	320,87	0,00					1942,48		0,545	Total
			Used (kg)	0,00	0,00	0,00	0,00	760,50	861,11	320,87	0,00					1942,48			production
Biocide 2		42TB014	Discharged (kg)	0,00	0,00	0,00	0,00	0,00	0,00	579,40	208,47					787,88		0,420	Total
			Used (kg)	0,00	0,00	0,00	0,00	0,00	0,00	579,40	208,47					787,88			production
Biocide			Discharged (kg)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1709,47					1709,47		-	Total
			Used (kg)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1709,47					1709,47			production
Gas treatment		68TB001	Discharged (kg)	0,00	4957,75	4754,50	3207,96	2586,80	38448,45	37744,39	48797,14					140495,99		0,024	Gas
			Used (kg)	8227,90	99155,02	95089,90	64157,82	51716,03	480060,56	47180,49	60996,43					474584,16			
Corrosion inhibitor		42TB015	Discharged (kg)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00					0,00		-	Oil
			Used (kg)	3298,67	45579,96	55169,91	43376,88	27007,71	23823,88	23062,46	0,00					221319,26			
Wax inhibitor			Discharged (kg)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00					0,00		-	
			Used (kg)	0,00	0,00	218,99	1388,28	0,00	0,00	0,00	0,00					1607,26			

Inventory of natural components in PW including heavy metals and BTEX-compounds.

Produced water													
		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Component	PW volume (m3)		12573,89	12630,8	18205,8	22255,8	26530,923	27963,47	20891,627				
Heavy metals													
Arsenic (As)	Concentration (g/m3)		0,0008005	0,0003172	0,0005	0,0005	0,0005	0,0002381	0,0005				
	Component (kg)		0,0100653	0,0040067	0,0091029	0,0111279	0,0132655	0,0066585	0,0104458				
Barium	Concentration (g/m3)		0,0054441	0,0233733	0,0087823	0,1602585	0,3098454	0,2115321	3,2396854				
	Component (kg)		0,0684533	0,2952236	0,159888	3,5666811	8,2204849	5,9151709	67,682297				
Iron (Fe)	Concentration (g/m3)		0,0003072	0,2307167	0,2619263	0,8929817	0,0056162	0,0096676	0,1140313				
	Component (kg)		0,0038625	2,9141369	4,768578	19,874022	0,1490017	0,2703394	2,3823				
Lead (Pb)	Concentration (g/m3)		0,00015	0,0001256	0,0001	0,0001695	0,0001323	0,0007884	0,000125				
	Component (kg)		0,0018861	0,0015868	0,0018206	0,0037724	0,0035108	0,0220477	0,0026115				
Cadmium (Cd)	Concentration (g/m3)		0,000025	4,937E-05	0,000075	0,000075	7,5E-05	0,000075	0,000075				
	Component (kg)		0,0003143	0,0006236	0,0013654	0,0016692	0,0019898	0,0020973	0,0015669				
Copper (Cu)	Concentration (g/m3)		0,000285	0,0013019	0,0008883	0,0003878	0,00025	0,00025	0,0013879				
	Component (kg)		0,0035832	0,0164445	0,0161727	0,0086315	0,0066327	0,0069909	0,0289961				
Chromium (Cr)	Concentration (g/m3)		0,0478368	0,0112946	0,0232479	0,051837	0,0003993	0,0002517	0,0016764				
	Component (kg)		0,6014942	0,1426593	0,4232458	1,1536747	0,0105945	0,0070386	0,0350225				
Mercury (Hg)	Concentration (g/m3)		4,815E-05	0,0002025	0,000445	0,0007264	0,0008887	0,000722	0,0004436				
	Component (kg)		0,0006055	0,0025574	0,008101	0,0161676	0,0235791	0,0201908	0,0092674				
Nickel (Ni)	Concentration (g/m3)		0,0016305	0,0028819	0,0718596	0,0858014	0,0052401	0,00075	0,0039983				
	Component (kg)		0,0205014	0,0364005	1,3082616	1,9095793	0,139024	0,0209726	0,0835312				
Zinc (Zn)	Concentration (g/m3)		0,0081213	0,0638782	0,1150264	0,0659673	0,0024271	0,002	0,0043966				
	Component (kg)		0,1021166	0,8068322	2,0941476	1,468156	0,0643936	0,0559269	0,0918516				
Sum	Concentration (g/m3)		0,0646484	0,3341413	0,4828507	1,2587048	0,3253742	0,226275	3,3663195				
	Component (kg)		0,8128823	4,2204715	8,7906836	28,013481	8,6324765	6,3274337	70,32789				
BTEX-compounds													
Benzen	Concentration (g/m3)		22,298947	12,607995	9,9050478	14,699857	26,555314	18,310935	16,791771				
	Component (kg)		280,38451	159,24907	180,32932	327,15707	704,53699	512,03728	350,80742				
Toluene	Concentration (g/m3)		21,982807	12,462283	10,112083	16,633288	23,964077	16,983563	16,270069				
	Component (kg)		276,4094	157,4086	184,09856	370,18714	635,78908	474,91936	339,90821				
Ethylbenzen	Concentration (g/m3)		1,2354999	0,6770019	0,6062178	0,8551808	1,1403624	0,8682833	0,87509				
	Component (kg)		15,535039	8,551076	11,03668	19,032732	30,254867	24,280214	18,282053				
Xylen	Concentration (g/m3)		8,054448	4,5145713	3,9581375	6,2317621	8,332508	6,3653603	6,5816586				
	Component (kg)		101,27574	57,022647	72,06106	138,69285	221,06912	177,99756	137,50156				
Sum	Concentration (g/m3)		53,571702	30,261851	24,581486	38,420088	59,992262	42,528142	40,518589				
	Component (kg)		673,60469	382,23139	447,52562	855,06979	1591,6501	1189,2344	846,49924				

Inventory of natural components in PW including PAH-componds.

Produced water													
		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Component	PW volume (m3)	12573,89		12630,8	18205,8	22255,8	26530,923	27963,47	20891,627				
PAH-compounds													
Naphtalene	Concentration (g/m3)		2,894291E+00	4,026662E+00	3,164498E+00	3,212941E+00	4,060456E+00	2,233382E+00	1,387309E+00				
	Component (kg)		36,392503	50,859533	57,61222	51,476365	107,72767	62,453129	28,983152				
C1-Naphtalene	Concentration (g/m3)		1,207427E+00	2,049568E+00	1,929068E+00	1,507185E+00	3,248637E+00	1,243112E+00	0,7338714				
	Component (kg)		15,182064	25,887847	35,12024	33,543615	86,18934	34,761748	15,331766				
C2-Naphtalene	Concentration (g/m3)		0,1975814	0,3152095	0,4621323	0,1742951	1,1822421	0,2400132	0,1102848				
	Component (kg)		2,4843665	3,9813487	8,413488	3,893098	31,365973	6,7116012	2,3040294				
C3-Naphtalene	Concentration (g/m3)		0,0553297	0,149078	0,2817805	0,0644513	0,7720577	0,0941969	0,0457078				
	Component (kg)		0,6957091	1,8829747	5,13004	1,4344163	20,483402	2,6340712	0,9549109				
Phenantrene	Concentration (g/m3)		0,0110448	0,0199549	0,017752	0,0047043	0,0572355	0,0102745	0,0036887				
	Component (kg)		0,1388763	0,2520459	0,3231886	0,1046987	1,5185115	0,2873115	0,0770623				
C1-Phenantrene	Concentration (g/m3)		0,005268	0,0115126	0,014289	0,0043431	0,0542654	0,0037562	0,0024486				
	Component (kg)		0,0662395	0,145413	0,2801418	0,0966584	1,4397118	0,1050351	0,0511555				
C2-Phenantrene	Concentration (g/m3)		0,0029274	0,0079502	0,0142592	0,004271	0,0054534	0,0025214	0,0024064				
	Component (kg)		0,0368093	0,1004177	0,259601	0,0950545	0,1446836	0,0705063	0,0502744				
C3-Phenantrene	Concentration (g/m3)		0,0004752	0,0013712	0,0059846	0,0023912	0,0054899	0,0003458	0,0006344				
	Component (kg)		0,0059757	0,0173191	0,1089547	0,0532172	0,145651	0,0096693	0,0132547				
Dibenzothiophene	Concentration (g/m3)		0,0009289	0,0016776	0,001405	0,0003565	0,0046831	0,0007853	0,0002826				
	Component (kg)		0,0116804	0,021189	0,0257787	0,0079332	0,1242472	0,0219595	0,0059037				
C1-Dibenzothiophene	Concentration (g/m3)		0,0023551	0,00188	0,0030826	0,0075723	0,0056741	0,0005997	0,0018721				
	Component (kg)		0,0296123	0,0237461	0,0561209	0,1685275	0,1505382	0,0167709	0,0391117				
C2-Dibenzothiophene	Concentration (g/m3)		0,0023551	0,00188	0,0030826	0,0075723	0,0056741	0,0005997	0,0018721				
	Component (kg)		0,0296123	0,0237461	0,0561209	0,1685275	0,1505382	0,0167709	0,0391117				
C3-Dibenzothiophene	Concentration (g/m3)		0,0001322	0,0001061	4,313E-05	0,0004991	0,0001645	3,433E-05	0,00002				
	Component (kg)		0,0016624	0,0013403	0,0007852	0,0111073	0,0043635	0,0009599	0,0004178				
Acenaphtylene	Concentration (g/m3)		0,000766	0,0013872	0,0010149	0,0006325	0,0031127	0,0007924	0,0004608				
	Component (kg)		0,0096317	0,0175215	0,0184765	0,0140763	0,0825835	0,0221577	0,009627				
Acenaphtene	Concentration (g/m3)		0,0023754	0,0046972	0,0037305	0,0024696	0,0067714	0,0029059	0,0016582				
	Component (kg)		0,0298686	0,0593289	0,0679172	0,0549619	0,1796502	0,0812596	0,0346425				
Anthracene	Concentration (g/m3)		2,777E-05	5,538E-05	5,427E-05	3,704E-05	0,0002962	2,317E-05	1,311E-05				
	Component (kg)		0,0003492	0,0006995	0,0009888	0,0008243	0,0078588	0,000648	0,0002738				
Fluorene	Concentration (g/m3)		0,0214021	0,0351593	0,0390359	0,0197838	0,1082209	0,0269855	0,0124866				
	Component (kg)		0,2691077	0,4440895	0,7106798	0,4403044	2,8712002	0,7546083	0,2608647				
Fluoranthene	Concentration (g/m3)		9,07E-05	0,0001499	0,0002842	0,0001105	0,0003852	2,65E-05	7,18E-05				
	Component (kg)		0,0011408	0,0018936	0,0051736	0,0023365	0,0102194	0,0007419	0,0014995				
Pyren	Concentration (g/m3)		6,202E-05	0,0001135	0,0001953	0,0001301	0,0005307	3,574E-05	0,0001185				
	Component (kg)		0,0007798	0,0014336	0,0035557	0,0028966	0,014081	0,0009994	0,0024758				
Chrysene	Concentration (g/m3)		7,92E-05	5,73E-05	0,0001093	0,00012	1,70E-05	0,0000105	0,0001105				
	Component (kg)		0,0009961	0,0007236	0,0019807	0,0026706	0,0004515	0,0001398	0,0023081				
Benzo(a)anthrasene	Concentration (g/m3)		1,21E-05	1,23E-05	2,76E-05	2,75E-05	5,63E-06	0,0000005	3,00E-05				
	Component (kg)		0,0001524	0,0001555	0,0005032	0,0006125	0,0001492	0,0001398	0,0006265				
Benzo(a)pyrene	Concentration (g/m3)		8,24E-06	1,23E-05	3,36E-05	4,28E-05	1,63E-05	0,0000005	8,57E-06				
	Component (kg)		0,0001036	0,0001555	0,0006117	0,000953	0,0004325	0,0001398	0,000179				
Benzo(g,h,i)perylene	Concentration (g/m3)		1,08E-05	2,21E-05	7,94E-05	0,0001208	3,91E-05	0,0000005	1,57E-05				
	Component (kg)		0,0001362	0,0002786	0,0014453	0,002688	0,001037	0,0001398	0,0003282				
Benzo(b)fluoranthene	Concentration (g/m3)		5,072E-05	4,412E-05	0,0001229	0,0001374	1,107E-05	0,00001	7,187E-05				
	Component (kg)		0,0006378	0,0005573	0,0022367	0,0030576	0,0002938	0,0002796	0,0015015				
Benzo(k)fluoranthene	Concentration (g/m3)		0,000005	0,000005	2,696E-05	1,608E-05	5,983E-06	0,0000005	0,000005				
	Component (kg)		6,287E-05	6,315E-05	0,0004908	0,0003579	0,0001587	0,0001398	0,0001045				
Indeno(1,2,3-c,d)pyrene	Concentration (g/m3)		6,94E-06	0,00001	2,12E-05	3,78E-05	1,39E-05	0,00001	1,00E-05				
	Component (kg)		8,73E-05	0,0001263	0,0003866	0,0008409	0,0003696	0,0002796	0,0002089				
Dibenz(a,h)anthrasene	Concentration (g/m3)		0,000005	1,72E-05	1,23E-05	4,71E-05	3,89E-05	0,0000005	0,000005				
	Component (kg)		6,29E-05	0,0002171	0,0002243	0,0010488	0,0010322	0,0001398	0,0001045				
Sum	Concentration (g/m3)		4,41E+00	6,63E+00	5,94E+00	4,11E+00	9,52E+00	3,86E+00	2,31E+00				
	Component (kg)		5,54E+01	8,37E+01	1,08E+02	9,16E+01	2,53E+02	1,08E+02	4,82E+01				

Inventory of natural components in PW including organic acids, phenols, radioactive compounds, and oil in water.

Produced water												
		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Component	PW volume (m3)		12573,89	12630,8	18205,8	22255,8	26530,923	27963,47	20891,627				
Organic acids													
Formic acid	Concentration (g/m3)		8,8933063	1,5361703	2,3277197	75,082852	1	1	1				
	Component (kg)		111,82346	19,40306	42,378	1671,0289	26,530923	27,96347	20,891627				
Acetic acid	Concentration (g/m3)		4,702888	2,9497102	9,0003625	50,80758	1,6372301	1,2051898	7,1033579				
	Component (kg)		59,133597	37,2572	163,8588	1130,7633	43,437226	33,70129	148,4007				
Propionic acid	Concentration (g/m3)		1,388583	1	2,0213229	9,9561158	1,0893549	1	1,7139143				
	Component (kg)		17,45989	12,6308	36,7998	221,58132	28,901591	27,96347	35,806457				
Butanoic/Buturic acid	Concentration (g/m3)		1	1	1	5,8955687	1	1	1				
	Component (kg)		12,57389	12,6308	18,2058	131,2106	26,530923	27,96347	20,891627				
Pentanioic/Valeric acid	Concentration (g/m3)		1	1	1	3,7197604	1	1	1				
	Component (kg)		12,57389	12,6308	18,2058	82,786243	26,530923	27,96347	20,891627				
Sum	Concentration (g/m3)		16,984777	7,4858805	15,349405	145,46188	5,726585	5,2051898	11,817272				
	Component (kg)		213,56472	94,55266	279,4482	3237,3704	151,93159	145,55517	246,88204				
Phenols													
Phenol	Concentration (g/m3)		51,405776	64,792391	46,750871	61,407868	73,944583	48,586932	39,779246				
	Component (kg)		646,37057	818,37973	851,137	1366,6812	1961,818	1358,6592	831,05316				
C1-Alkyl phenols	Concentration (g/m3)		84,558003	68,25983	49,963737	43,841294	38,395882	34,13211	32,205809				
	Component (kg)		1063,223	862,17627	909,6298	975,72307	1018,6782	954,45225	672,83175				
C2-Alkyl phenols	Concentration (g/m3)		22,891336	17,73372	10,975689	14,343206	17,361094	11,078733	9,9835755				
	Component (kg)		287,83314	223,99107	199,8212	319,21952	460,60584	309,79982	208,57313				
C3-Alkyl phenols	Concentration (g/m3)		11,980972	11,822824	6,1736655	7,7458662	8,9671618	5,6101478	6,2744303				
	Component (kg)		150,64742	149,33172	112,39652	172,39045	237,90708	156,8792	131,08306				
C4-Alkyl phenols	Concentration (g/m3)		2,8222834	2,0408768	1,3989723	1,205061	1,9255454	1,2235445	0,9304301				
	Component (kg)		35,487081	25,777907	25,46941	26,819597	51,086496	34,214549	19,438199				
C5-Alkyl phenols	Concentration (g/m3)		0,4249541	0,4207221	0,2553837	0,2002312	0,3530294	0,2113325	0,1443718				
	Component (kg)		5,3433263	5,3140567	4,649464	4,4563063	9,3661962	5,9095901	3,0161621				
C6-Alkyl phenols	Concentration (g/m3)		0,0038093	0,0031605	0,002475	0,0008428	0,0011176	0,0007523	0,0005749				
	Component (kg)		0,0478981	0,0399194	0,0450586	0,0187571	0,0296519	0,0210382	0,0120116				
C7-Alkyl phenols	Concentration (g/m3)		0,0015045	0,0017683	0,0026092	0,0007018	0,0069087	0,0010684	0,0005466				
	Component (kg)		0,0189176	0,0223348	0,0475026	0,01562	0,183294	0,0298753	0,0114202				
C8-Alkyl phenols	Concentration (g/m3)		0,0002923	0,0001703	4,41E-05	8,40E-05	0,0003722	7,70E-05	6,02E-05				
	Component (kg)		0,0036757	0,0021514	0,0008026	0,0018702	0,0098736	0,0021531	0,0012568				
C9-Alkyl phenols	Concentration (g/m3)		0,0002995	0,00052	8,127E-05	6,125E-05	5,433E-05	4,775E-05	8,38E-05				
	Component (kg)		0,0037665	0,006568	0,0014797	0,0013632	0,0014415	0,0013352	0,0017508				
Sum	Concentration (g/m3)		174,08923	165,07598	115,52353	128,74522	140,95575	100,84475	89,319129				
	Component (kg)		2188,9788	2085,0417	2103,1982	2865,3278	3739,6861	2819,969	1866,0219				
Radioactive compounds													
Ra-226	Concentration (g/m3)		577,81912	584,51682	494,46083	1115,7991	323,76883	552,35134	447,97461				
	Component (kg)		7,265434	7,382915	9,002055	24,833001	8,5898858	15,44566	9,3589184				
Ra-228	Concentration (g/m3)		340,56119	486,62761	467,54869	512,99154	398,58663	488,11567	243,7584				
	Component (kg)		4,282179	6,146496	8,512098	11,417037	10,574871	13,649408	5,0925095				
Pb-210	Concentration (g/m3)		383,29033	403,8517	336,2942	331,07755	190,07274	264,65953	241,32869				
	Component (kg)		4,8194505	5,10097	6,122505	7,3683957	5,0428051	7,4007989	5,0417489				
Th-228	Concentration (g/m3)		0	0	0	0	30,712409	0	0,5836056				
	Component (kg)		0	0	0	0	0,8148285	0	0,0121925				
Sum	Concentration (g/m3)		1301,6706	1474,9961	1298,3037	1959,8682	943,1406	1305,1265	933,64531				
	Component (kg)		16,367064	18,630381	23,636658	43,618434	25,02239	36,495867	19,505369				
Oil in water													
	Oil (C7-C40) (mg/l)		13,184777	8,6344301	17,935117	10,681294	58,327683	8,2182453	6,088567				
	Authority requirement (30 mg/l)		30	30	30	30	30	30	30				
	Internal requirement (15 mg/l)		15	15	15	15	15	15	10				

Inventory of chemicals discharged during well interventions on the Vega field.

Chemicals discharged during well interventions														
Description function group	Details		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021 Cumulative	Colour code
Island Frontier															
Friction reducing agent	Well intervention P.-13	Discharged (kg)							47,93					47,93	
		Used (kg)							159,75					159,75	
Hydrate inhibitor		Discharged (kg)							333,90					333,9	
		Used (kg)							6678,00					6678	
Hydraulic liquid		Discharged (kg)							1446,00					1446	
		Used (kg)							1981,00					1981	
Other chemicals		Discharged (kg)							0,00					0	
		Used (kg)							68000,00					68000	
Island Wellserver															
Hydrate inhibitor		Discharged (kg)						0						0	
		Used (kg)						16700						16700	
Hydraulic liquid		Discharged (kg)						0						0	
		Used (kg)						64						64	
SEVEN VIKING															
Hydrate inhibitor		Discharged (kg)						0						0	
		Used (kg)						66780						66780	
Scale dissolver		Discharged (kg)						0						0	
		Used (kg)						14160						14160	
Hydrate inhibitor		Discharged (kg)						0						0	
		Used (kg)						49730						49730	
Other chemicals		Discharged (kg)						0						0	
		Used (kg)						85850						85850	
Edda fauna															
Scale inhibitor		Discharged (kg)							0					0	
		Used (kg)							450,68					450,68	
		Discharged (kg)							0					0	
		Used (kg)							10344					10344	
		Discharged (kg)							0					0	
		Used (kg)							10,164					10,164	
Hydrate inhibitor		Discharged (kg)							0					0	
		Used (kg)							172380					172380	
pH-control		Discharged (kg)							0					0	
		Used (kg)							21679					21679	
Antifreezer		Discharged (kg)						5008,5	0					5008,5	
		Used (kg)						5008,5	30105					35113,5	
Corrosion inhibitor		Discharged (kg)						903						903	
		Used (kg)						903						903	
Other chemicals		Discharged (kg)						6226,864						6226,864	
		Used (kg)						6226,864						6226,864	
		Discharged (kg)						235,3						235,3	
		Used (kg)						235,3						235,3	
		Discharged (kg)						3124,8						3124,8	
		Used (kg)						3124,8	0					3124,8	
		Discharged (kg)							0					0	
		Used (kg)						20520	389025					409545	
		Discharged (kg)							0					0	
		Used (kg)							130					130	
		Discharged (kg)							0					0	
		Used (kg)							56100					56100	
		Discharged (kg)							0					0	
		Used (kg)							10060,74					10060,74	
		Discharged (kg)						1670						1670	
								1670						1670	

Inventory of field production data, allocation keys and PW discharged including expected volumes in 2021.

Field production data

Net calorific values (MJ/Sm3):
Vega and Gjøa gas = 41400,00 (from 2010)
Net calorific value, oil = 3672,50 (from 2010)
Vega condensate = 38500,00 (from 2013)
33975,00 (2010-2012)
Gjøa oil = 33371,38 (from 2015)
33455,59 (in 2014)
33740,77 (in 2013)
36762,50 (2012-2012)

		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Cumulative
Vega														
OIL	Volume (m3)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00				0,00
	Energy (MJ)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00				0,00
CONDENSATE	Volume (m3)	17984,00	658305,00	852772,04	999977,38	1151776,74	1057986,53	853723,13	563857,14	120344,53				6276726,48
	Energy (MJ)	611006400,00	22365912205,13	28972929957,08	40399085,95	44343404374,50	40732481584,80	32868340335,99	21708499925,81	4633264531,67				196276238400,90
GAS	Volume (Sm3)	21779576,00	896813304,48	1259488678,82	1773528266,21	2001667941,64	2007597075,79	1977603797,78	1522103787,36	374316491,85				11834898919,94
	Energy (MJ)	901674446,40	37128070805,39	52142831303,31	73424070221,05	82869052784,00	83114518937,84	81872797228,28	63015096796,85	15496702762,44				489964815285,56
Gjøa														
OIL	Volume (m3)	125917,00	2161477,91	2828828,30	1978338,30	1474726,93	1346049,42	1216054,74	835406,83	210105,78				12176905,2
	Energy (MJ)	4629023712,50	79461331776,66	103994800231,70	66750657839,20	49337863509,54	44919526733,09	40581424763,87	27878678707,72	7011519654,22				4,24565E+11
CONDENSATE	Volume (m3)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00				0,00
	Energy (MJ)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00				0,00
GAS	Volume (Sm3)	94460348,00	2123548504,28	3552651118,51	4561979052,13	4120710241,31	4527941185,89	4839774987,55	4287212038,18	1576608798,30				29684886274
	Energy (MJ)	3910658407,20	87914908077,19	147079756306,40	188865932758,22	170597403990,30	187456765095,65	200366684484,64	177490578380,82	65271604249,77				1,22895E+12
Total production														
OIL	Volume (m3)	125917,00	2161477,91	2828828,30	1978338,30	1474726,93	1346049,42	1216054,74	835406,83	210105,78				12176905,20
	Energy (MJ)	4629023712,50	79461331776,66	103994800231,70	66750657839,20	49337863509,54	44919526733,09	40581424763,87	27878678707,72	7011519654,22				424564826928,50
CONDENSATE	Volume (m3)	17984,00	658305,00	852772,04	999977,38	1151776,74	1057986,53	853723,13	563857,14	120344,53				6276726,48
	Energy (MJ)	611006400,00	22365912205,13	28972929957,08	40399085,95	44343404374,50	40732481584,80	32868340335,99	21708499925,81	4633264531,67				196276238400,90
GAS	Volume (Sm3)	116239924,00	3020361808,76	4812139797,34	6335507318,34	6122378182,95	6535538261,68	6817378785,34	5809315825,55	1950925290,15				41519785194,10
	Energy (MJ)	4812332853,60	125042978882,58	199222587609,71	262290002979,28	253466456774,30	270571284033,49	282239481712,92	240505675177,66	80768307012,21				1718919107035,75
OIL EQUIVALENTS	Volume (Sm3 o.e.)	260140,92	5840144,72	8493740,13	9313822,99	8748881,85	8939574,22	8887156,65	7208579,80	2281375,60				59973416,88

Allocation keys calculated relative to Vega production

		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
OIL+CONDENSATE	Volume (m3)	0,12	0,23	0,23	0,34	0,44	0,44	0,41	0,40	0,36			
	Energy (MJ)	0,12	0,22	0,22	0,00	0,47	0,48	0,45	0,44	0,40			
GAS	Volume (Sm3)	0,19	0,30	0,26	0,28	0,33	0,31	0,29	0,26	0,19			
	Energy (MJ)	0,19	0,30	0,26	0,28	0,33	0,31	0,29	0,26	0,19			
TOTAL PRODUCTION	Volume (Sm3)	0,19	0,30	0,26	0,28	0,33	0,31	0,29	0,26	0,19			
	Energy (MJ)	0,15	0,26	0,24	0,22	0,37	0,35	0,32	0,29	0,22			

Produced water discharged from Vega and Gjøa

		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Reported volumes													
VEGA	Volume (m3)		12573,89	12630,8	18205,8	22255,8	26530,92	27963,47	20891,63				
GJØA	Volume (m3)	375	101156	107167,9	175618,1	266785	474983,2	740002,8	812787,4				
Total reported	Volume (m3)	375	113729,89	119798,7	193823,9	289040,8	501514,1	767966,3	833679				
Predicted volumes (RNB numbers)													
Total predicted	Volume (m3)												421140
Vega predicted	Volume (m3)												160600