North Sea Energy
offshore system integration

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North Sea Energy 2020-2022

Safety Integrity & Reliability of offshore hydrogen production installations

North Sea Energy 2020-2022

Unlock the low-carbon energy potential North Sea with optimal value for society and nature

The North Sea Energy program and its consortium partners aim to identify and assess opportunities for synergies between energy sectors offshore. The program aims to integrate all dominant low-carbon energy developments at the North Sea, including: offshore wind deployment, offshore hydrogen infrastructure, carbon capture, transport and storage, energy hubs, energy interconnections, energy storage and more.

Strategic sector coupling and integration of these low-carbon energy developments provides options to reduce CO2 emissions, enable & accelerate the energy transition and reduce costs. The consortium is a public private partnership consisting of a large number of (international) partners and offers new perspectives regarding the technical, environmental, ecological, safety, societal, legal, regulatory and economic feasibility for these options.

In this fourth phase of the program a particular focus has been placed on the identification of North Sea Energy Hubs where system integration projects could be materialized and advanced. This includes system integration technologies strategically connecting infrastructures and services of electricity, hydrogen, natural gas and CO2. A fit-for-purpose strategy plan per hub and short-term development plan has been developed to fast-track system integration projects, such as: offshore hydrogen production, platform electrification, CO2 transport and storage and energy storage.

The multi-disciplinary work lines and themes are further geared towards analyses on the barriers and drivers from the perspective of society, regulatory framework, standards, safety, integrity and reliability and ecology & environment. Synergies for the operation and maintenance for offshore assets in wind and oil and gas sector are identified. And a new online Atlas has been released to showcase the spatial challenges and opportunities on the North Sea. Finally, a system perspective is presented with an assessment of energy system and market dynamics of introducing offshore system integration and offshore hubs in the North Sea region. Insights from all work lines have been integrated in a Roadmap and Action Agenda for offshore system integration at the North Sea.

The last two years of research has yielded a series of 12 reports on system integration on the North Sea. These reports give new insights and perspectives from different knowledge disciplines. It highlights the dynamics, opportunities and barriers we are going to face in the future. We aim that these perspectives and insights help the offshore sectors and governments in speeding-up the transition.

We wish to thank the consortium partners, executive partners and the sounding board. Without the active involvement from all partners that provided technical or financial support, knowledge, critical feedback and positive energy this result would not have been possible.

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Executive summary

The North Sea Energy 4 program consists of seven work packages, as shown in Figure 1.1. This report provides the work performed in the third work package Safety, Reliability and Integrity. This work package has three main sections:

1. Further evaluation of safety concerns that were highlighted in the HAZID study presented in the previous phase (NSE3);
2. Highlight the attention points related to the asset integrity and asset safety of various components of the (hydrogen generation) system;
3. Apply the gained knowledge in design iterations together with the platform design team of work package 1 (WP1).

The first part of the report describes the identification of the safety concerns of hydrogen production on an offshore platform. Both new installations and partial re-use of an existing offshore installations are considered. Visuals summarizing the various aspects have been developed. In the visuals, the offshore installations are divided into the foundation structure and the topside structure, and for each of these different safety and integrity considerations are listed. The visuals can be used when reviewing or developing standards to determine if all systems are covered in standards, or in pre-liminary designs to check if all systems have been regarded.

Based on the outcome of the HAZID study of the NSE3 program, analyses have been performed to calculate the (safety) effect distances for an accidental release or vent of oxygen or hydrogen using dedicated software. The studied scenarios are based on design information from WP1 and discussions with project partners. This quantification of consequences for releases of oxygen or hydrogen after production and before injection to the pipeline requires attention since the generated hydrogen and oxygen amounts that are considered in this program are relatively high compared to existing solutions or other pilot projects. The effect distances and heights found for the venting scenarios can be used in the design process for determining the location and height of the vent stack. The determined distances did not give reason for major changes in the platform design.

The final part of the work is about applying the gained knowledge to the platform design for the Hub West region of the North Sea. This work is not explicitly reported because it is directly incorporated in the platform designed by work package 1 (WP1).

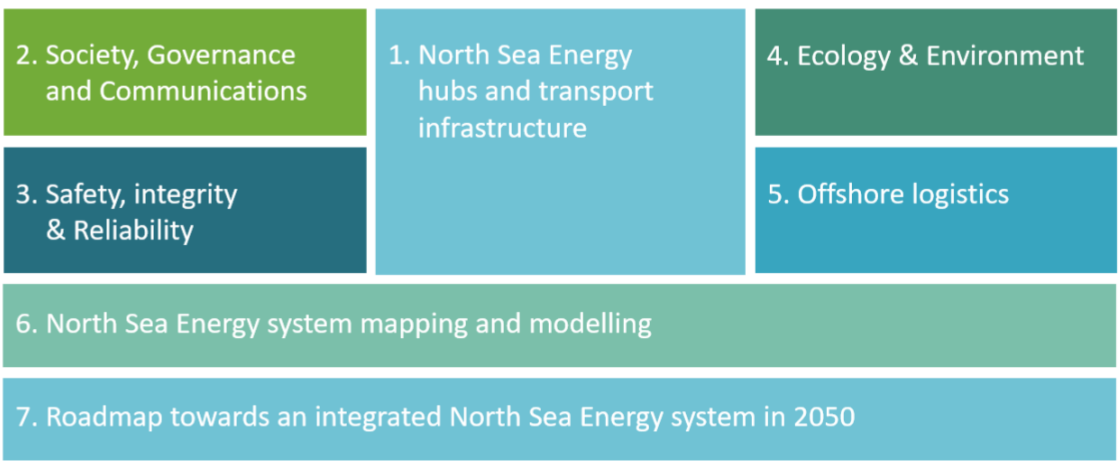

Figure 1.1 Work package scheme in the North Sea Energy 4 program

1 Introduction

1.1 Background

The electric power produced by the wind turbines fluctuates due to the irregular nature of the wind power. One option to counteract the imbalances of the supply from the wind turbines and the demand of the grid is by harnessing the surplus energy to produce energy carriers, such as hydrogen, that can be converted back to electricity when needed, for example by means of a fuel cell. Transport of hydrogen is less energy consuming than transport of electricity over a long distance which will be driver for the future more remotely located wind parks. In addition, hydrogen is an energy carrier with a very high combustion energy density (142 MJ/kg compared to 22.5 MJ/kg for ammonia, 55 MJ/kg for methane [1]) which makes it an alternative for energy storage and transport.

Using electricity to generate hydrogen molecules is known as *power-to-hydrogen* technology. Particularly in the offshore domain, use of power-to-hydrogen systems is viable due to the close vicinity to renewable energy generated by the wind parks, access to water and existing infrastructure such as gas transport pipelines or gas production platforms. The North Sea Energy (NSE) program [2] aims at investigating different perspectives of making North Sea region a pivot in the energy transition future of Europe. Figure 1.1 shows the currently investigated power-to-gas (P2G) conversion system scenario.

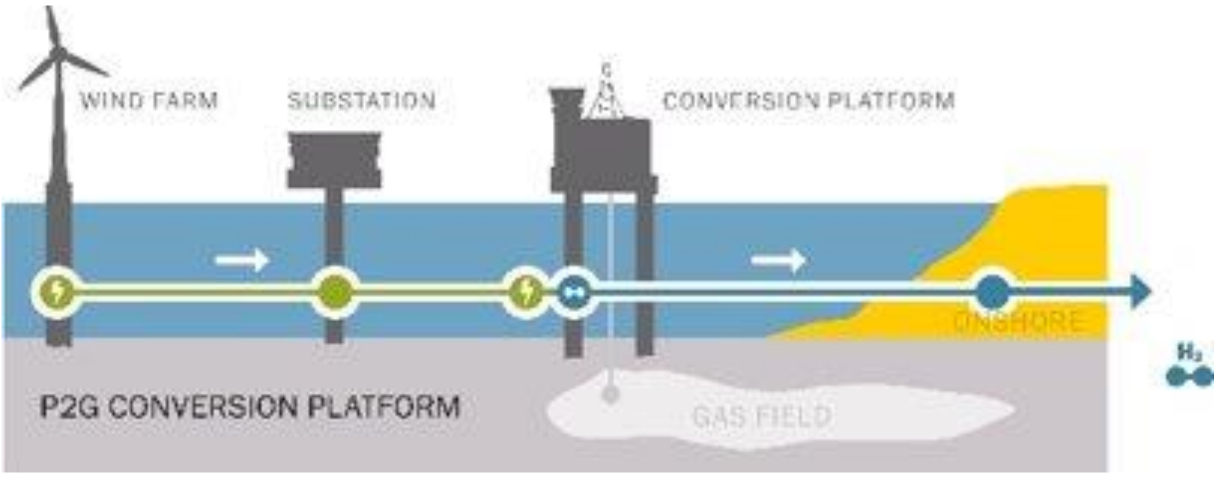

Figure 1.1 System scenario

As a continuation of the NSE3 program, which was focussed on the feasibility of producing hydrogen offshore, the aim NSE4 is to investigate the possibility of large-scale hydrogen production offshore.

The workflow described in this document is the safety, integrity, and reliability of offshore hydrogen generation installations. As the technology of the electrolyser is not known in detail, reliability of the hydrogen production and transport have not been considered in full detail. In the studies of the current report, reliability aspects partially have been taken into account.

In 2019, a first screening of the risks associated with the offshore hydrogen production and storage is made, and a report is published giving an overview of the functional safety of offshore hydrogen production [3]. The report contains a hazard identification (HAZID) study for a selected scenario. The result of HAZID is the identification of different type of hazards and a list of necessary actions to mitigate such risks. The NSE program continues with further evaluating the safety and integrity of selected scenarios and this report outlines the results of this work package (WP3).

1.2 Aim of the study

The main goal of evaluating safety and integrity for (large scale) hydrogen production is subdivided to three main sub-goals:

1. Further evaluation of safety concerns that were highlighted in the HAZID study presented in the previous phase (NSE3);
2. Highlight the attention points related to the asset integrity and asset safety of various components of the (hydrogen generation) system;
3. Apply the gained knowledge in design iterations together with the platform design team of work package 1 (WP1).

The methodology of this work package is elaborated in the first report of this work package in 2021 [4]. This work package focusses on the North Sea region and the assets in this region, however the methodology can be applied outside of this region as well. The provided safety assessment in this work package is generic for the North Sea region, for any type of hydrogen installation, and any legal framework. In a later stage, the safety assessment will be applied to a specific scenario (energy hubs) as defined in the NSE4 program. The continuation of the safety concerns given in the HAZID study of the NSE3 program is also specific for this scenario. Sub-goal three is not explicitly mentioned in this work package, but is a continuous combined effort supporting the design team of WP1 and is therefore implicitly included in the final platform design of WP1.

1.3 Work package scope

This work package (WP3) focusses on the safety and integrity of offshore installations for hydrogen (H2) generation. The scope starts at the input of the electricity feed and ends at the offloading of the produced gases. A by-product of the generation of hydrogen (using electrolysis) is oxygen (O2). The safety and integrity implications of the introduction of both hydrogen and oxygen on an offshore installation is investigated in this work package. A complete risk assessment will not be performed. Risk assessment methods for offshore installations are widely available and vary [5]. The current study will point out elements in the risk assessment which are changed or introduced due to the introduction of hydrogen on an offshore installation.

The scope ends at the offloading of the produced gases, and therefore pipelines are out of scope. A structural integrity assessment and study on the monitoring of pipelines for the use of hydrogen is performed by HINT in work package 1 (WP1). A complete state-of-the-art overview and gap analysis for the safety and integrity of injecting hydrogen in pipelines is given by PRCI [6]. Several safety and risk assessments of onshore pipelines for the transport of hydrogen are publicly available. A comparison of the probability, consequence, and risk of natural gas and hydrogen gas leakage in the onshore pipeline infrastructure is given by DNV GL [7]. A quantitative risk assessment (QRA) of hydrogen gas amongst others in onshore pipelines is given by Tebodin Netherlands B.V. [8].

Changes in the safety and integrity of offshore installations by the introduction of hydrogen and oxygen in gaseous media and the necessary systems to generate and offload these gases are the scope of the current work package. The generation of other energy carriers than H_2, such as and not limited to derivates of hydrogen: ammonia (NH_3) or synthetic methane gas (CH_4), are out of scope of this project.

An artificial island is given in the methodology report of WP1 as a possible location of hydrogen generation [9]. The safety and integrity assessment of an onshore facility is fundamentally different, and therefore out of scope of the current work package. However, for the consequence analysis of oxygen releases, this configuration was taken into consideration.

The NSE4 program also focusses on carbon capture and storage (CCS) [9]. In such a scenario, carbon-dioxide (CO_2) is captured onshore, exported to an offshore platform and stored in depleted offshore oil and gas fields. Offshore installations used for CCS are out of scope for the safety and integrity assessment as performed in the current report.

By law, safety regulations should be provided and followed to assure the safety and integrity of offshore installations. In the NSE3 program, it was already shown that the current legal framework at international, EU, and national level is not clear about the classification of generation of hydrogen or other power-to-gas installations [10]. For Dutch law, the difference is that if hydrogen generation installations are governed by electricity legislation, Rijkswaterstaat will provide safety regulations for the utility companies producing offshore electricity, while if hydrogen generation installations are governed by gas legislations, State Supervision of Mines (SSM) (Dutch: Staatstoezicht op de Mijnen) will provide the safety regulations as offshore regulator. Legal regulations of hydrogen generation installations are out of scope of the current work package and are researched in work package 2 (WP2). All installations should be safe and reliable, independent on the legal framework. WP2 also researches whether all necessary norms and standards are in place for the generation of hydrogen offshore. Therefore, standardization is out of scope of the current work package.

From a workshop concerning the HAZID study performed in NSE3 [3], a list of recommendations is presented [11]. Many recommendations should be investigated further in the design process, when specific equipment is known. These recommendations are considered in the safety assessment study in this report. Other recommendations contain roughly the actions to investigate either explosions or fire of hydrogen and its effect on the structural integrity, or dispersion of venting or accidental releases of oxygen and hydrogen gas. The latter is investigated in the current research and (partly) considers several actions of the list of recommendations given [11].

1.4 Report scope and lay-out

This report is on safety and integrity of system integration options. Chapter 2 presents design assumptions and starting points for the NSE4 project, including the scenario definition of the Hub West region in the North Sea. Chapter 3 gives the necessary steps for the safety and integrity assessment of offshore installations for hydrogen generation. This chapter corresponds to sub-goal 2 of the aim of this study as presented in section 1.2. Chapter 4 revisits the HAZID study from NSE3 and highlights the important information for the current research. Chapter 5 presents the consequences of a continuous release of the produced oxygen on an offshore platform and a production island. Chapter 6 presents the consequences of a release of the produced hydrogen on an offshore platform. The latter two subjects are a continuation of the evaluation of one of the safety concerns as highlighted by the HAZID study in NSE3, corresponding to sub-goal 1 of the aim of this study as presented in section 1.2. Chapter 8 will contain the conclusions and recommendations in the final report.

2 Design assumptions and considerations

This chapter discusses the design assumptions and considerations for the integrity and safety assessment of offshore installations used for hydrogen generation in North Sea. Different regions in the North Sea are considered in the NSE4 program by WP1. In this study, "Hub West" is selected to be further evaluated in WP3 to evaluate its safety and integrity. Section 2.1 presents general design assumptions and starting points. Section 2.2 gives design assumptions and starting points specific for the Hub West scenario. More information about Hub West can be obtained from the WP1 report.

At the moment this study was performed, the electrolyser technology was not fully known, and assumptions on the generation of hydrogen offshore and its transport via pipeline systems to shore were made. Therefore, full safety studies could not be conducted. This report is based on the assumptions mentioned in the current chapter specifically.

2.1 General

In the current study, the offshore installation for hydrogen generation is assumed to be electrified, meaning that a separate installation for electrification is assumed to be present, on which transformers are located to transform the high voltage power input coming from e.g. a wind park to a feed which can be used as input for the electrolyser system. The safety evaluation in this work starts with the assumption that hydrogen generation installation is intended to be partial re-use of an existing installation, or a new build structure. Only re-use of the foundation (or primary) structure is considered.

Hydrogen and oxygen are the output of the electrolysis, however offshore storage of these gases is not considered in this work. Only a small buffer storage for oxygen and hydrogen is necessary for the compressors to operate. Hydrogen is continuously offloaded by injecting it into a pipeline. Legally, at the moment of writing, a maximum mixture of 0.02 or 0.5 mol% hydrogen in natural gas is allowed in onshore pipelines [10][1]. For the onshore receiving equipment, a limitation of 15 vol% hydrogen in natural gas is expected [10]. In this report, this limitation is not taken into account.

Oxygen can be released via venting, transported via pipelines or ships, released to subsea, however for the consequence assessment only the continuous venting scenario is evaluated. For the scenario of CCS, current oil and gas installations present at wells are re-used for storage of CO_2 in the well[2]. CO_2 will be transported to the installation at the well via pipelines[1]. It is assumed that each function of CO_2 capture and storage, H_2 generation, electrification is located on a separate platform. Activities related to previous functions of re-used installations are considered to be ceased.

In general the following equipment is necessary for a hydrogen generation installation:

- High voltage transformer and rectifier
- Input: high voltage alternating current electricity feed from Wind Park Operator or national grid. Output: low voltage direct current electricity feed (<1kV).
- Desalination equipment
- Input: electricity feed, sea water. Output: deionized water.
- Electrolyser

[1] Pipelines are out of scope for the current work package, but mentioned here for completeness
[2] CCS is out of scope for the current work package, but mentioned here for completeness

- Input: electricity feed, fresh water. The assumed output in pressure is for oxygen and hydrogen at 30 barg for a PEM electrolyser and at 12-20 barg for an alkaline electrolyser.
- Compressor (pump), dryer, deoxidizer (if required by electrolyser technology)
- Cooling equipment
- Small storage of hydrogen/oxygen for compressors
- Piping
- It is assumed that all piping equipment, including valves, seals, et cetera, are designed for the intended gas.
- Access equipment, such as a helideck, lifting crane, and a boat landing facility depending on the purpose of the installation
- All equipment that handles hydrogen is assumed to be certified for its purpose and therefore safe.

2.2 Hub West scenario

Various regions of the North Sea are evaluated in terms of their techno-economic feasibility in the WP1 of the NSE4 program, including the "Hub West" scenario [9]. Hub West region is selected to be further evaluated in WP3 to evaluate its safety and integrity. This section gives the scenario of power-to-hydrogen gas for the Hub West region in the North Sea. Hub West covers a major part of the western part of the Dutch continental shelf. This area covers e.g., activities within the K/L blocks for oil & gas E&P licenses, wind developments around and on top of Ijmuiden Ver, Hollandse Kust Noord (HKN) and other potentially planned tendering areas south of the Cleaver Bank. Since this area is located close the border with the UK Continental Shelf, potential international interconnection could be foreseen. Figure 2.1 gives a visual representation of the Hub West area and storyline.

WP3 takes the suggested platform as a legged, manned installation structure and the electrical feed from the offshore substation (OSS) (either HKN or Ijmuiden Ver) or the national grid. This originates from the activities of WP1.

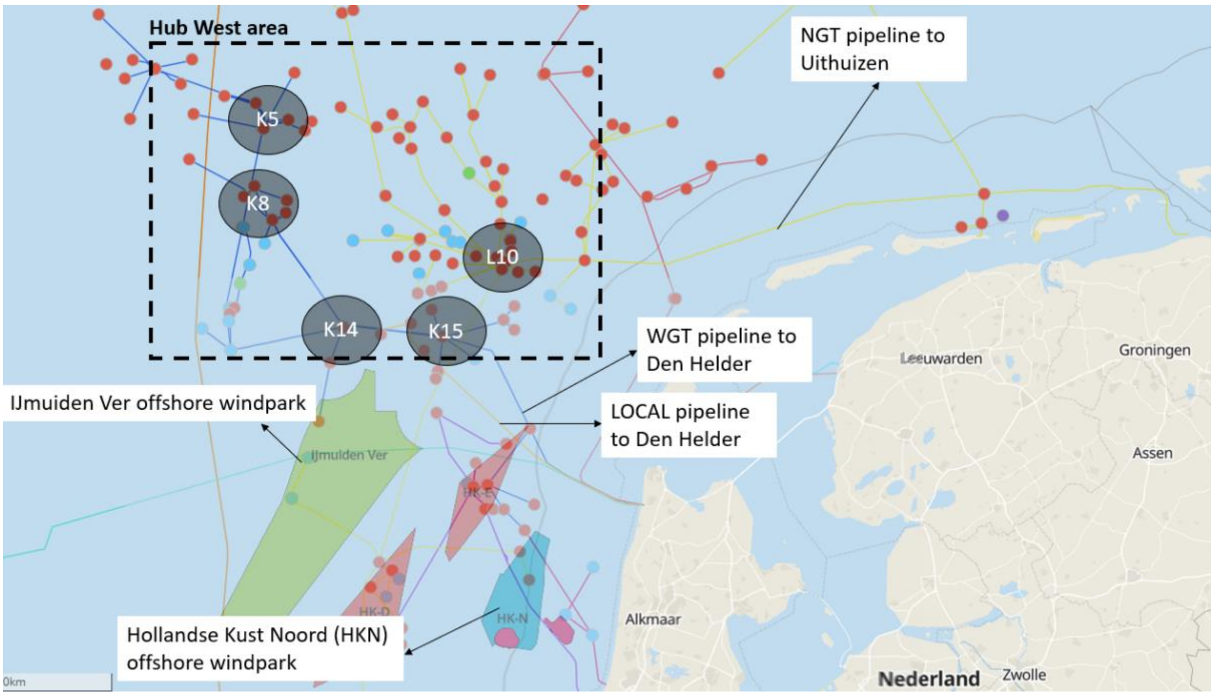

Figure 2.1 Visualization of Hub West storyline and area (black dashed box)

According to the Hub West scenario, the following steps are taken to generate hydrogen and oxygen from electricity, vent oxygen and transport hydrogen to shore:

- Electrification of the platform(s) has a feed from offshore wind farms (HKN, IJmuiden Ver, later on wind farms in the UK).
- The exact location is unknown within the Hub West area. The safety of the exact location for the environmental conditions have not been assessed.
- Transformation of electricity at a new build offshore platform. The main feed of 66 kV alternating current (AC) is input in the platform. The voltage for the electrolyser needs to be rectified to Direct Current (DC) and transformed to a lower voltage, which depends on the selected technology of the electrolyser and other topside equipment. The hydrogen generation platform is assumed to be electrified as starting point of the safety and integrity assessment.
- Hydrogen generation with a capacity of 500MW at a new build platform located close to offshore wind farm (OWF) offshore sub-station (OSS) is considered. Multiple of such platforms could be located in close vicinity to create a larger capacity. The electrolyser will be a polymer electrolyte membrane (PEM) electrolysis installation.
- New pipeline(s) for hydrogen from hydrogen generation platform(s) to L10-AP, K5/K8/K14/K15 or a new platform. This platform is used as compression platform, at which hydrogen is collected, compressed and injected. All current oil and gas production wells connected to platforms around L10-A complex and K5/K8/K14/K15 complex are assumed to be accessible, so not (yet) plugged.
- Re-use of platform foundation structure is regarded in the safety analysis in this report, also for the hydrogen production platform, to create a complete overview, even though it is considered in WP1 only for the compression platform.
- For the research in the NSE4 program, it is chosen to investigate the case of using the L10-A riser platform as compression platform, and offloading via the existing NoordGas Transport pipeline (NGT) [1]. Hydrogen is injected at an assumed pressure of 60 barg in the NGT pipeline from L10-A riser platform to shore (Uithuizen). The operational pressure of the NGT pipeline at landfall is 50 barg. In the NGT pipeline, hydrogen will be mixed with natural gas for as long as the natural gas production sustains. It is assumed over the years of the production life that mixture will change to a higher hydrogen content, after which 100% hydrogen will be transported.

For the consequence study, it is assumed that 49 kWh of electricity results in 1 kg hydrogen and 8 kg oxygen, which for a 500 MW PEM installation results in large production flows of both hydrogen and oxygen: 1.2 10^5 Nm^3/h of hydrogen and 6.1 10^4 Nm^3/h (22.7 kg/s) of oxygen.

The value of 49 kWh for 1 kg hydrogen is based on an efficiency of the PEM of 68% and a lower heating value of hydrogen of 120 MJ/kg [12]. After the calculations have started, based on expected impact of innovations by Siemens, it has been found that it is expected that the PEM efficiency will increase to 78% [13]. This efficiency only includes the PEM, not the complete system. Also, it can be assumed that this efficiency decreases over time due to degradation of the system. Therefore, the used efficiency might not be completely conservative, but will not be significantly off.

Platform lay-out

The platform lay-out is described by WP1 [13], WP3 took the available information as input during generation of this report. A process flow diagram of the hydrogen installation is provided by WP1 in Appendix A . More detailed information on the current lay-out considerations can be found in the report of WP1 [13].

[1] When an existing pipeline is used for hydrogen transport, it should be investigated whether this pipeline is suitable for hydrogen gas, and an inspection should verify the pipeline condition. Pipelines are out of scope of the current report.

3 Safety and integrity assessment

This chapter discusses the safety and integrity assessment of offshore hydrogen generation platforms. Design assumptions and starting points are given in Chapter 2. The given assessment is based on general considerations, not on the Hub West scenario, such that the assessment will be useable for all types of assets for hydrogen generation in the North Sea.

Table 3.1 gives relevant properties of methane, Groningen natural gas and hydrogen gas. Groningen natural gas consists for 81.3 vol% of methane, and 14.35 vol% of nitrogen [14]. From the given numbers, it is shown that the difference between methane and natural gas is limited. The gas and energy densities show that hydrogen has a low energy density per volumetric unit, while a large energy density per weight unit compared to natural gas. Further on, the table shows that the flammability limit range of hydrogen is significantly larger than for natural gas, mostly due to the flammability of hydrogen at large volumetric percentages. The table also shows that the minimum required energy to ignite hydrogen gas is significantly lower for hydrogen than methane gas, and that when an explosion occurs, the flame speed and therefore pressure wave speed is significantly higher for hydrogen than methane gas. These numbers show that hydrogen is a hazardous gas and therefore show the importance of safety and integrity of an installation in which hydrogen is generated.

Table 3.1 Comparison of relevant properties of methane, natural gas and hydrogen.

Properties	Unit	Methane	Groningen natural gas[3]	Hydrogen
Gas density (20 °C, 1 atm) [1]	kg/m^3	0.651	0.833	0.0838
Energy density (15 °C, 1 atm) [1]	kJ/m^3	32,560	31,669	10,050
Auto ignition temperature[2]	°C	595	617	560
Minimum ignition energy[2]	mJ	0.23		0.017
Upper flammability limit[2]	Vol.%	17.0	16.6	77.0
Lowest flammability limit[2]	Vol.%	4.4	4.7	4.0
Limiting oxygen concentration[2]	Vol.%	9.9		4.3
Maximum rate of pressure rise at explosion[2]	bar*m/s	52		800

[1] From [15]
[2] From [16]
[3] From [14]

Section 3.1 points out elements in the safety assessment of offshore installations, which are changed or added due to the introduction of hydrogen. The elements are listed per barrier, according to the framework of safety and environmental critical elements. Section 3.2 provides a visual which combines all identified elements.

3.1 Changes in the safety and integrity assessment due to the introduction of hydrogen

Safety and Environmental Critical Elements (SECEs) have been introduced in the safety and integrity assessment of offshore oil and gas installations in the legislation of the United Kingdom after the Piper Alpha incident in 1988, to prevent such a major incident from happening again. SECEs are defined as the equipment, plant or software which prevents, controls or mitigates against the effects of Major Accident Hazards (MAHs), including the result of a subsequent Major Environmental Incident (MEI) [17]. Shell applies the same definition to Safety Critical Elements (SCEs) in [18]. Offshore directive 2013/30/EU as implemented in the Dutch Mining Act requires companies to define SECEs and manages them via specific approved procedures as part of the Health and Safety Executive (HSE) case (RIGG). State Supervision of Mines (SSM) (Dutch: Staatstoezicht op de Mijnen) is the offshore authority for wind energy, carbon capture and storage (CCS), and oil and gas exploration and production in the North Sea under Dutch legislation. As noted in Section 1.3, it is not clear whether an offshore hydrogen generation installation is applicable to SSM regulations. Because there is no specific regulatory framework for risk assessment of offshore hydrogen generation assets available, the SECEs framework will be applied here. The SECEs relatable to offshore assets in the North Sea which are changed or added due to the introduction of hydrogen on the installation are listed in this section per barrier. A complete list of SECEs is given in Appendix B . For every identified SECE, a bowtie analysis could be created. Bowties are often used in safety assessment to assess risks in the risk assessment matrix. For the current report, it is too detailed to provide bowtie analyses for all SECEs. The following SECEs are discussed in the following sections:

- Structural integrity components
- Process containment systems
- Ignition control systems
- Detection control systems
- Process containment relief systems
- Protection systems
- Shutdown systems
- Navigational aids
- Rotating equipment
- Escape, evacuation and rescue equipment
- Communication systems

The main hazards that are faced by an offshore structure could at least include:

- vessel (ship) collisions,
- dropped objects,
- fires and explosions, and
- abnormal environmental actions, including seismic loads and accidental loads.

3.1.1 Structural integrity components

The first identified SECE, is the foundation or primary structure. The function of the foundation or primary structure is to provide and maintain structural integrity under all expected actions through service life, and to provide sufficient robustness to maintain availability of critical systems during a major incident [18].

The foundation or primary structure of a hydrogen generation platform can be a floating or fixed foundation. The choice for a foundation type depends mostly on the water depth at the location. Generally, the structure types are:

- Floating structure: semi-submersibles, spar, floating-leg, FPSO[1,2]
- Fixed at seabed: jacket, monotower, tension-leg platform[3]

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[1] Floating structures are not used in Dutch continental waters, but are implemented in other parts of the North Sea.
[2] Definitions of floating structure types can be found in NEN-EN-ISO 19904:2019 [36]
[3] Definitions of fixed structure types can be found in NEN-EN-ISO 19902:2020 [35]

If a foundation or primary structure is re-used for a new function, such as hydrogen generation, a structural integrity assessment needs to be performed, this could be done as per ISO 19901 series of standards.

- This (re-)assessment is visualized in Figure 3.1. The assessment consists of a static, and dynamic check. As input, the added weight and design envelope for the new functionalities, and the historic design envelope and current condition of the structure needs to be known. For the static check, the new weight due to the new top side installation is compared with the load carrying capacity of the current state of the structure. For floating structures, also the buoyancy of the structure needs to be evaluated. For the dynamic check, the combination of new weight and design envelope is compared to the remainder of fatigue lifetime as given by the current state of the structure and historic design envelope. The dynamic check should also take vibrations into account, when heavy rotating equipment is present in the installation. If both the static load carrying capacity, and the fatigue lifetime is sufficient, the foundation structure is fit for service for the new function.
- If the foundation or primary structure is new build, the structure is designed for function, and therefore no re-assessment based on the new function is necessary.

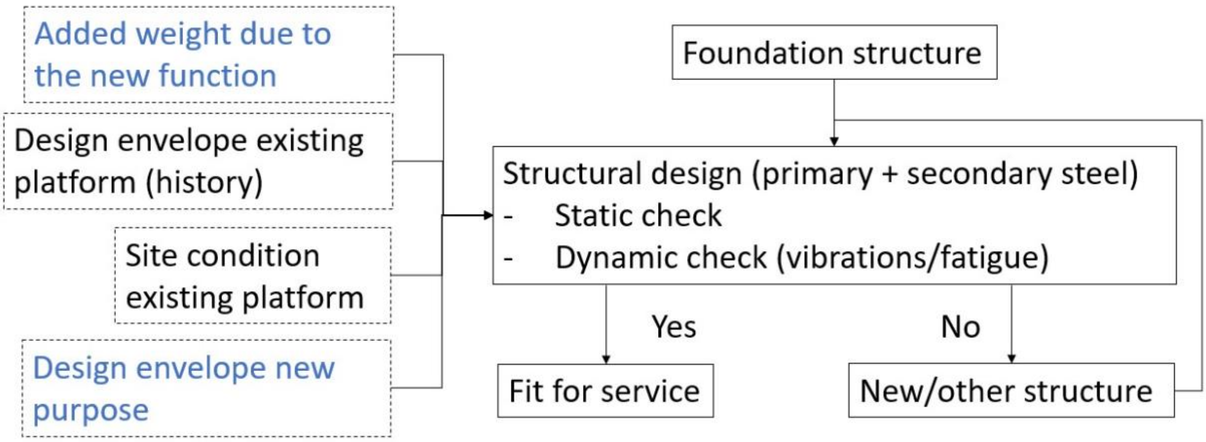


Figure 3.1: Visual for re-assessment of structural integrity of foundation structure for re-use

The topside structure, or surface primary structure has the same function for the safety and integrity of the installation as the foundation or primary structure. The topside should provide protection for systems and persons in case of a dropped object. To assess the effects of a dropped object onto a part of the structure, a dropped object risk assessment should be performed. In general, this assessment is not changed due to the presence of hydrogen and oxygen. For every component that can result in a release of hydrogen or oxygen, a dropped object risk assessment is necessary. The consequences of an accidental release of hydrogen or oxygen is discussed in Chapter 3. To prevent accidental releases, the location of transport and storage of hydrogen and oxygen in the installation should be chosen as such, where possible, that the pathway of the lifting crane is not over this equipment, or that the topside, or surface primary structure is reinforced at these locations.
If venting is used as offloading or release method for oxygen, the vent stack height needs to be determined using an analysis as described in Chapter 3. After an oxygen release, oxygen could flow back to offshore installation, which results in oxidation of steel components. This should be taken into account. Because of the oxidation risk, an oxygen venting stack could have a significant height. The venting stack should be marked as hazardous area and should be included in the risk assessment of crane operations according to EN 13852: 'Cranes - Offshore cranes - Part 1: General-purpose offshore cranes'.

The centre of gravity will be changed due to the introduction of equipment for hydrogen generation, which could have impact on several load assessments.

Hydrogen contains more energy per mass than natural gas, and therefore a higher pressure increase rate, as shown in Table 3.1. Therefore, a blast wall design study should be performed for hydrogen gas. Design of blast walls is done accordingly HSE report [19], but no specific method for hydrogen gas is given. Finite element modelling should be used to determine blast wall thicknesses.

3.1.2 Process containment systems

The process containment system consists of all systems in which hydrogen or oxygen is present. One type of such equipment consists of an electrolyser, storage tank, the piping system, and compressors. The safety function of this type of equipment is to ensure leak tight integrity and maintain integrity of the pressure envelope. Since hydrogen molecules are very small compared to other molecules, the permeability of hydrogen through materials is relatively high. Also, certain materials are susceptible for degradation due to the presence of hydrogen. Therefore, dedicated material suitable for hydrogen should be selected in all process containment systems. If the process containment systems fail, potentially in combination with another major incident, a mixture of hydrogen and oxygen should be prevented, because this decreases the minimum ignition energy. Therefore, storage of both gases should be as far apart as possible. Since all activities related to previous functions of re-used installations are considered to be ceased, no natural gas is assumed to be present at the hydrogen generation installation.

All process containment systems should be designed accordingly pressure equipment directive 2014/68/EU and ATEX directive 2014/34/EU and underlying harmonised standards (UKCA is currently considered as equal).

The ISO Technical Report ISO/TR 15916:2015 - 'Basic considerations for the safety of hydrogen systems'; is a guideline that should be considered in the design of the pressure containment system.

3.1.3 Ignition control systems

Hydrogen gas requires a small amount of energy to ignite, even when only a small amount of hydrogen is mixed with air, as shown in Table 3.1. Therefore, is of importance to prevent hydrogen to be mixed with air, and to locate any ignition sources as far away from the hydrogen source as possible, which is the function of ignition control systems. Chapter 5 of the biennial report on hydrogen safety of the HySafe consortium discusses hydrogen safety barriers and safety measures which includes more in-depth information on ignition control systems [20].

Aspiration (i.e. blowing air through a(n) (enclosed) space) is a method to prevent that the percentage of hydrogen in the environmental exceeds the lowest flammability limit. For offshore platforms or other installations, the equipment handling explosive/flammable gases are located in naturally aspirated spaces, such that the leaked gas is dispersed into the atmosphere. Active aspiration by means of fans is generally not used because it is dependent on electricity feed or break down due to other reasons. The emergency shutdown system should be activated when the active aspiration system fails. Therefore, natural aspiration, by locating the equipment in open air, or by openings in floors, walls, and roofs, is used. Note that natural or active aspiration does not effectively disperse hydrogen into the atmosphere in case of an accidental release due to a failure of piping, storage tank, or a blow-down. Natural aspiration is mainly used for the dissipation of heat in the surrounding air due to the electrolysis equipment (PEM cells), or high voltage transformers and rectifiers. Depending on the electrolyser technology, the electrolyser could be located in an enclosed space in which an overpressure is applied. This way the corrosive environment due to sea water is excluded from the electrolyser equipment to ensure the integrity of the system.

Purging is normally applied in piping systems containing flammable mixtures with an open connection to the atmosphere (cold vent). A positive gas flow, the “purge gas”, is to keep the oxygen (from the atmosphere) out of a system containing flammable components to prevent explosion in the piping system. As the only intention of a purge gas is to keep the oxygen out, this may be done with any gas, flammable (H_2, natural gas) or not (inert; N_2), as long as it does not chemically react with the “flammable gas”. A similar system can be applied on atmospheric tanks containing flammable mixtures. Here, a small overpressure, created by pressure control valves, is created with a “blanketing gas”. Again, like purge gas, this gas can be any gas as long as it keeps the oxygen (from the atmosphere) out. For the hydrogen piping on an offshore installation, purging is not necessary because it is enclosed and designed to continuously handle hydrogen, although it could be useful for maintenance purposes.

An inert gas can also be used create a non-flammable environment around a system that contains flammable gases such as hydrogen. This is called gas blanketing and is used in enclosed spaces only. Because natural aspiration is used on offshore installations, such a system is not necessary.

The number of ignition sources should be reduced as much as possible. Possible ignition sources are electrical equipment, due to sparks. All electrical equipment and other sources of ignition should be certified for the specific type of area. The area of an explosive gas atmosphere should be classified accordingly the international standard IEC 60079 part 10-1. Hydrogen gas is incorporated in this standard. Next, article 8 of ATEX 153 (99/92/EG) provides regulations to design a space protected for explosion risks[1].

3.1.4 Detection control systems

Human senses can’t detect hydrogen, because hydrogen gas is odourless and colourless. A detection control system should be implemented when handling flammable gases. If a controlled burn-down scenario is possible (see Section 3.1.6), a detection control system is not preferred to reduce the number of possible sources of ignition. The safety function of a fire and gas detection control system in a hydrogen installation is to detect all hydrogen and oxygen gas accumulations (prevention) and all fires (mitigation) and initiate an executive action. Fire detection systems are different than for natural gas, because hydrogen burns with very pale blue flames and emits neither visible light in daytime (sun radiation can overpower the hydrogen flame light) nor smoke [20]. Fire and flame detection system should be designed accordingly the American standard API RP14 G: ’Recommended Practice for Fire Prevention and Control on Fixed Open-type Offshore Production Platforms‘. The gas (leakage) detection system should be designed for detection of hydrogen and oxygen gas. The alarm functions of the detection control system should include automatic shut-down of the hydrogen flow. The gas detection system generally is set at 10% of the lowest flammability limit. As shown in Table 3.1, the lowest flammability limit is 4 vol.% hydrogen in air, so the gas detection system is set at 0.4 vol.% hydrogen in air. Several types of gas and fire detection equipment for hydrogen is discussed in the previous North Sea Energy project [3], and in the less recent HySafe report [20].

Electro-magnetic fields, if strong enough, can have health effects [21], but also affect the functionality of systems such as detection systems. To reduce the effect of EMFs on human beings, a protection system should be designed to reduce the EMF. The EMF can be tested using IEC 62110:2009: 'Electric and magnetic field levels generated by AC power systems - Measurement procedures with regard to public exposure’ and IEC 62041:2017: ’Transformers, power supplies, reactors and similar products -

[1] Following Dutch regulations specifically, an ‘aanvullende risico inventarisatie en evaluatie’ (ARIE) needs to be performed, and an ‘explosieveiligheidsdocument’ (EVD) needs to be composed [37].

EMC requirements', assuming the incoming electric feed is AC and a voltage of larger than 20 kV. The transformer design should be compliant to IEC 60076 series. An acceptable EMF (the acceptance criteria) can be determined from CISPR TR 18-3:2017 RLV: 'Radio interference characteristics of overhead power lines and high-voltage equipment - Part 3: Code of practice for minimizing the generation of radio noise' and IEC 61000-6-4:2018 RLV: 'Electromagnetic compatibility (EMC) - Part 6-4: Generic standards - Emission standard for industrial environments'.

3.1.5 Process containment relief systems

Process containment relief system are designed to protect equipment and piping under pressure from over or under pressurisation to maintain containment during a process upset condition or major incident. Also the offloading system is included in this barrier.

The venting system for oxygen and hydrogen should be separated systems. Venting systems and pressure relief systems should be design accordingly API Standard 521/ISO 23251: 'Pressure-relieving and De-pressuring Systems'. This standard is applicable to hydrogen.

The offloading system is defined as the transport of produced gases from the offshore installation to shore. The offloading of oxygen could be either via pipeline, vessel, releasing it subsea, or venting. For offloading via pipeline or vessel, injection equipment should be present including a compressor to ensure a certain injection pressure. For the design of such equipment special considerations should be applied for material choice since oxygen is a reactive gas. For a release of oxygen subsea, the environment should be considered. There is no experience yet with subsea release of oxygen (on a large scale). Next to looking at the environment, releasing substantial amounts of oxygen subsea results in a lower density of the water, and therefore can be dangerous for ships because it decreases the ships buoyancy. For now it is recommended to offload oxygen in a different manner. Venting oxygen can be a risk for aviation or marine traffic, and can result in oxidation of the steel of the offshore installation, or increase the flammability of materials on the platform when oxygen flows back to the installation. The environmental risk of a cloud with increased oxygen concentration should be further researched. It is known that the release of oxygen is a risk for humans for a certain concentration. When a living quarter is located on the platform, the oxygen concentration should be acceptable close to the inlet of the HVAC system of the living quarter or any other location where people are present. Aviation is not possible in oxygen enriched air, because of oxidation of the helicopter. A risk assessment needs to be performed before a helicopter can be safely landed on the helicopter deck. This risk assessment should (at least) include the wind direction, wind speed, amount of oxygen release, and the helicopter descent route. An helicopter evacuation will be high risk and critical and should therefore be investigated per case. Due to the risk of oxidation of the steel used in/on the hydrogen generation installation, the vent stack height for oxygen would be relatively high, as already mentioned in Section 3.1.1. ISO 4126-1: 'Safety Devices for Protection against Excessive Pressure can be used for the design of an oxygen venting stack. By pre-mixing the oxygen with air, the risk could be reduced. Further research on venting of oxygen is performed in Chapter 5.

Hydrogen is transported to shore via a pipeline. In emergencies (for example reaching the lowest flammability limit due to a leakage), hydrogen should be able to be released via venting, flaring, or by releasing it into a fuel cell. Because of the risk on backfire, a flaring stack cannot be used to flare large quantities of hydrogen (see the relatively high maximum rate of pressure rise at explosion in Table 3.1). For very small quantities, and a high velocity flow, flaring into the atmosphere is possible using special nozzles. Hydrogen could also be released in a fuel cell which is used to generate electricity from hydrogen. For very high-capacity hydrogen generation installations, controlled flaring could be considered using this method. Venting of hydrogen is also possible and is already applied onshore. American standard CGA

G-5.5 is used to design hydrogen vent systems. When a living quarter is located on the platform, the hydrogen cloud should not be able to reach to the inlet of the HVAC system of the living quarter or any other location where people are present. Further research on venting of hydrogen is performed in Chapter 6.

Hydrogen should never be vented at the same moment as venting of oxygen. If these gases mix, this results in a more explosive gas cloud which could explode mid-air or close to the installation. Hydrogen and oxygen should also have separate venting stacks for emergency releases.

A PEM electrolyser requires filtered fresh water as input. Fresh water is distilled from sea water using a fresh water maker, which filters out salts and minerals using reversed osmosis. Next to filtered fresh water, this process outputs a mixture of water, minerals, and salts with a higher temperature and larger concentration of salts/minerals then sea water. This mixture is referred to as a brine solution. The brine solution can either be discharged into the sea directly, or treated before being discharged (either offshore or onshore). The main concerns or risks of a direct brine discharge into the sea are environmental. The higher temperature, higher salinity, and an output velocity can have a negative effect on the ecosystem [1]. The designed fresh water maker system results in a concentration increase of 27% in the brine solution compared to sea water [13]. At full capacity, the brine solution has a flow rate of 375 m3/h. In further research, the effects from this increased concentration and volumes should be quantified. When the effects appear to be unacceptable, the water could be pre-mixed with sea water before discharge into the sea. A diffuser system can be used to spread the brine solution over a larger area. For a discharge into a water body, a permit is required for which an immission analysis is to be performed according to the Dutch *Waterwet* (per January 1st 2023 *Omgevingswet*) [2]. Chemicals used for cleaning the filters should not be on the list of substances of very high concern of the RIVM (Dutch: *Lijst Zeer Zorgwekkende Stoffen*) [22]. These chemicals are probably of very small amounts, such that an immission analysis will not cause any issues.

Sea water is used on the hydrogen production platform for the production of filtered fresh water and for the use of cooling water. Therefore, a water inlet will be located subsea. A water inlet introduces two environmental risks: (i) bumping of larger marine organisms, and (ii) entrapment of smaller marine organisms [1]. There are no standards or guidelines available for design of a subsea water inlet to mitigate these risks. The effects of a water inlet on the marine environment needs to be investigated further. A water inlet could also be overgrown by organisms, which induces the risk that the inlet is (partly) blocked. Chemicals are used to clean the inlet from organisms. These chemicals may not be on the list of substances of very high concern of the RIVM [22], and an immission analysis should be performed according to the Dutch *Waterwet*.

3.1.6 Protection systems

The safety function of protection systems is to limit the effect or mitigate the consequence of a fire and/or an explosion. This includes passive protection systems, such as application of non-flammable materials and isolation, coatings, protection walls, and active protection systems, such as inert gas injection, and fire extinguish equipment.

A controlled burn-down scenario of the installation can be considered when the installation is normally unmanned, no aviation and shipping is present at and around the installation, and when there is insignificant environmental impact. When a controlled burn-down scenario is not possible, the installation should have (passive/active) fire protection, an evacuation plan and a rescue plan.

The 2016 edition of NFPA 2 '*Hydrogen Technologies Code*' consolidates the latest fire and life safety requirements applicable to the generation, installation, storage, piping, use, and handling of hydrogen in compressed gas form or cryogenic liquid form. Further on, the passive fire protection should not impose any additional safety risks, e.g., hydrogen could settle in isolation material.

An ignited gas leakage is hard to extinguish, and therefore prevention and mitigation systems are of more importance than fire extinguish systems. This is general for offshore gas installations.

Flame arrestors need to considered as per ISO 16852:2016 "*Flame arresters — Performance requirements, test methods and limits for use*".

3.1.7 Shutdown systems

The safety function of shutdown systems is to achieve a safe shutdown of plant and equipment, to prevent or mitigate the consequences of the release of a major hazard or a process upset/abnormal event. Emergency shutdown valves contribute to the isolation of flammable or hazardous gases and equipment. Blowdown valves release gases to a safe location to reduce pressure or reduce the amount of gas at a certain location. Both hydrogen and oxygen are vented in a blowdown scenario. API 521/ISO 23251 is used to design a shutdown system.

The shutdown system is initiated by the detection system at a certain percentage of hydrogen or oxygen or when a fire is detected. The design of the complete safety system is done accordingly ISO 10418:2019 '*Petroleum and natural gas industries — Offshore production installations — Process safety systems*', which refers to API RP 14C.

3.1.8 Navigational aids

There is nothing new within this barrier due to hydrogen introduction.

3.1.9 Rotating equipment

There is nothing new within this barrier due to hydrogen introduction.

3.1.10 Escape, evacuation and rescue equipment

The safety function of escape, evacuation and rescue equipment is to save lives in case of a major incident. If the hydrogen generation installation is unmanned, this equipment is not necessary. After a major incident, when evacuation is imminent, personnel is grouped at temporary refuge/primary muster areas. These locations should not be close to any flammable gases. The escape or evacuation routes go via lifeboats, helicopter, or worst-case scenario via jumping off the installation into the sea. Boat landing facilities and helicopter landing facilities are necessary. As mentioned in Section 3.1.2, when oxygen is vented, a risk assessment needs to be performed before aviation near the vent is possible. Therefore, it is of importance that oxygen is not vented at the moment a helicopter is needed for evacuation.

3.1.11 Communication systems

All communication systems should be ATEX II C compliant for use in an installation where hydrogen is present, such that the communication system will not be an ignition source.

3.2 Combined safety and integrity assessment visual

Based on the identified safety and environmental critical elements in Section 3.1, this section presents a combined visualization for a safety and integrity assessment of an offshore installation for hydrogen generation. Two separate visuals are presented, to include the difference in new build structures, and the partial re-use of structures. It is assumed that only the foundation structure and/or topside primary/secondary steel structure is re-used, and that all other equipment is new and designed for function. Therefore, the difference between the two figures, is found in the left side of the diagram, below ‘Foundation structure’. Figure 3.2 presents the visual for the partial re-use of existing structures, and Figure 3.3 presents the visual for new build structures. Blue text indicates elements changed due to hydrogen generation.

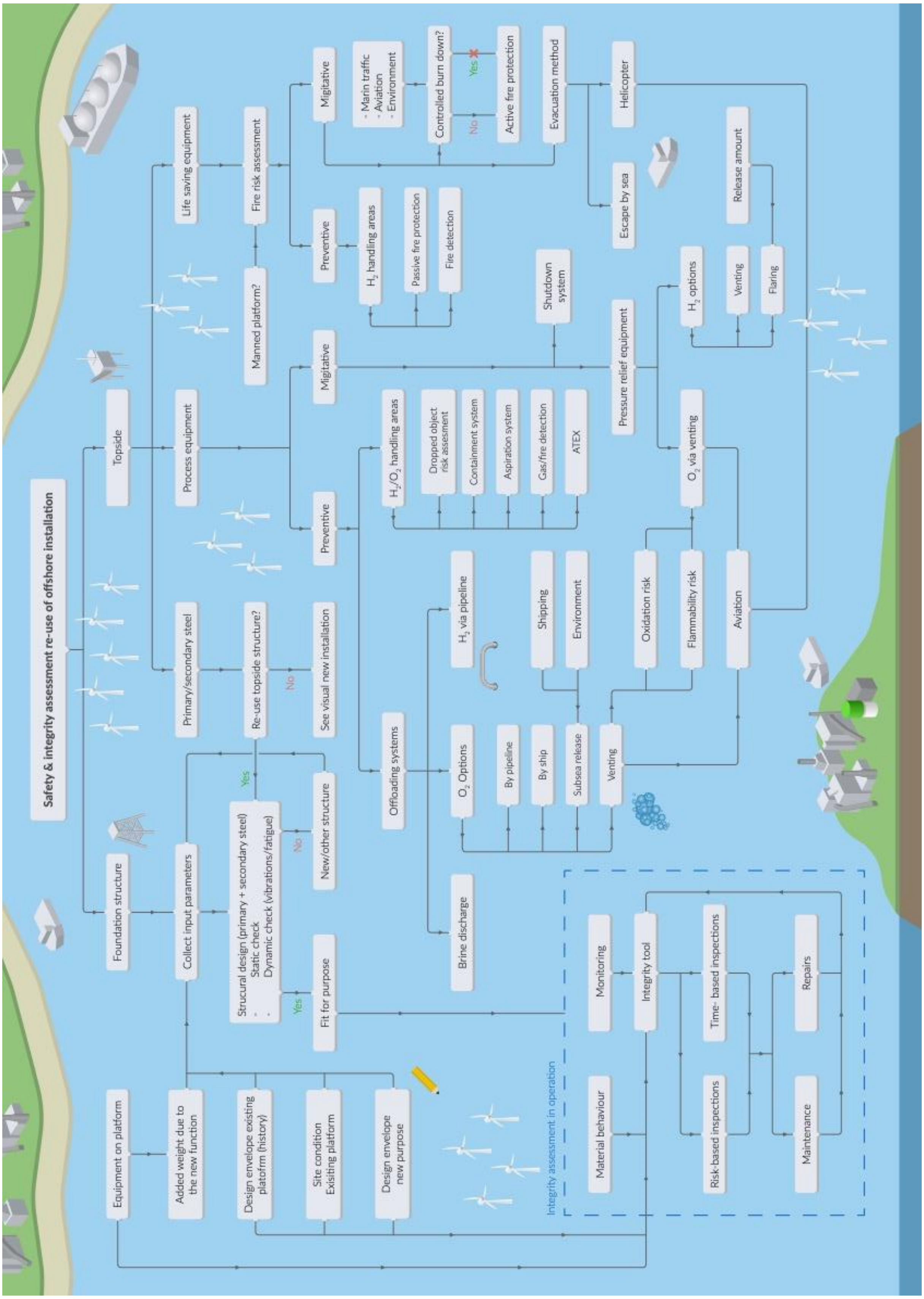


Figure 3.2 Visual on safety and integrity assessment for re-use of an offshore installation for hydrogen generation (as new function)

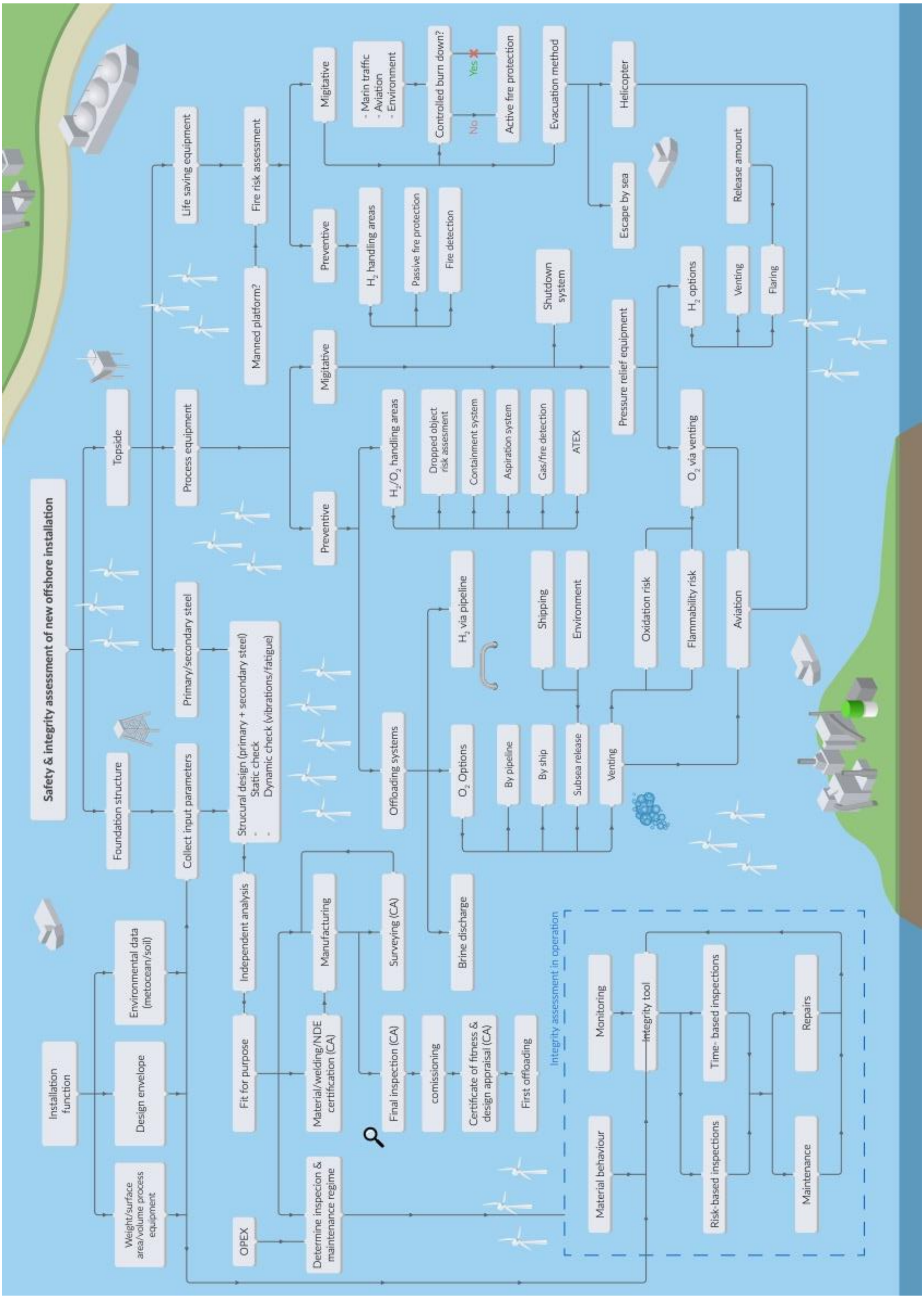


Figure 3.3 Visual on safety and integrity assessment of a new offshore installation for hydrogen generation

3.3 Re-use of the foundation structure of an existing platform

To be able to re-use the foundation structure of an existing platform from a safety point of view, a static and dynamic assessment need to be performed together with an investigation on the structural condition of the foundation structure. The static check is for the ultimate load on the foundation structure, and the dynamic check for dynamic loads on the structure (e.g. wind, waves and vibrations). This is indicated in the visual for re-use of existing structures in Figure 3.2. In this paragraph a comparison is made between characteristics of interest for the static and dynamic check of current platforms in the North Sea and a 500MW capacity hydrogen generation platform as designed in WP1 of the NSE4 program.

A database of specifications of Dutch offshore platforms in the North Sea is obtained from OSPAR (international convention between governments and the EU to protect marine environments) [23]. To determine the suitability to re-use the foundation structure of the given platforms for a 500MW capacity hydrogen generation platform, the platform topsides are compared to the topside of the platform as designed in WP1 of the NSE4 program. The latter platform is estimated to have a topside weight of approximately 9500 megaton and a surface of 70 by 40 meter [24]. This is a significant topside weight compared to oil and gas production platforms currently in the North Sea. Currently, 14 Dutch offshore platforms in the North Sea are designed for a topside weight of 9500 megaton or higher according to the OSPAR database. Specifications of these 14 platforms are listed in Appendix D .

Next to the load carrying capacity, one should look at the fatigue life of the existing foundation structure in combination with the load of the new structure. For most platforms the operation lifetime is about 30 years according to the Ecoinvent database [25], but many oil & gas platforms have been in the North Sea for a longer time period. The operation lifetime is different than the fatigue lifetime of the structure. The design life of the 500MW hydrogen generation platform as designed is taken as 50 years by WP1 and WP4 in the NSE4 program. All Dutch offshore platforms with a topside mass of over 9500 megaton in the North Sea have been constructed before 2000. Therefore over 20 years of fatigue loading has passed for these structures. This impacts the fatigue damage in the foundation structure, but could have also impacted the condition of the structure (corrosion, marine fouling, et cetera).

It can be concluded, that although the load carrying capacity may be sufficient (static check), the fatigue lifetime (dynamic check) of existing Dutch offshore platforms may not be sufficient for a 500 MW hydrogen production topside for a lifetime of 50 years. The ISO 19901 series of standards can be used for (re-)assessment of an offshore structure.

4 HAZID study validation

In the North Sea Energy 3 program a HAZard IDentification study has been performed [3]. The goal of this HAZID study was to:

- identify potential hazards and reasonably foreseeable accident events which could lead to escalation, injuries to personnel or fatalities, asset damage and environmental impact; with focus on the differences between a typical gas production platform and the intended change-over to a hydrogen producing platform;
- identify engineering and / or procedural safeguards already incorporated into the design that will help reduce the likelihood or the severity of consequences related to the identified threat;
- and identify any actions required to help reduce the risk from the threats identified for the future design.

In the current study in the NSE4 program, the HAZID study is re-evaluated. All actions identified in the HAZID study as given in report [3], which is attached to this report in Appendix C , are evaluated. There are several differences in starting points between NSE3 and NSE4, which are addressed in evaluating the actions resulting from the HAZID study. The main differences are listed in Table 4.1.

Table 4.1 Main differences between starting points in NSE3 and NSE4

	NSE3	NSE4
Platform general	Re-use of a typical gas production platform	New build platform specifically designed for hydrogen production (WP1 assumption)*
Number of platforms	Single platform	Single platform or configuration of several equal platforms in proximity interlinked by bridges.
Platform lay-out	All equipment on one platform including hotel facility (temporal refuge)	Pressure equipment on separate platform for all configurations. When a configuration of multiple platforms is chosen, not all platforms will have a hotel facility.
Capacity	100 MW	500 MW

* In the overall work for NSE4 the option of re-use has not been taken into account, for WP 3 this option is considered. The current chapter focusses on the overall picture of NSE4.

All actions identified in the HAZID study are validated by structuring it in the following categories:

1 Action is a design aspect and should be regarded in the design process. In the NSE3 program, re-use of an existing typical natural gas production platform was considered. Therefore several identified HAZID items are not valid as HAZID item in the NSE4 program, but part of the design.

2 Action is already covered in current standards or in the study of NSE3.

3 Action should be further evaluated in the current study.

4 Action is not valid or of interest for the current starting points.

Table 4.2 provides the results of the evaluation of the recommended actions following from the HAZID study in NSE3. The actions which should be further evaluated in the current study, are either on continuous release of oxygen or accidental release of hydrogen. The former will be further investigated in Chapter 5, and the latter in Chapter 6.

Table 4.2 Recommended actions from HAZID study in NSE3 program, evaluated for the starting points of the NSE4 program.

Action no.	Recommended action	Evaluation
[1]	Consider H2 detection and shutdown and depressurization	1
[2]	Perform a dispersion study on ventilation for H2	3 (See Chapter 6)
[3]	Consider minimising the H2 inventory	1
[4]	Investigate the blast peak of an explosion in respect to hydrocarbon explosions and impact on blast wall	2
[5]	Investigate if personal detection of H2 is required	3 (See Chapter 6)
[6]	Investigate if O2 measurement can detect O2 releases	2
[7]	Investigate the dispersion of O2	3 (See Chapter 5)
[8]	Consider to install PEM in a controlled environment with forced ventilation	1
[9]	Reduce O2 pressure as close to PEM electrolyser as possible	1
[10]	Investigate the impact on personnel health and safety requirements of high oxygen levels	3 (See Chapter 5)
[11]	Install fire detection suitable for H2 fires	1
[12]	Investigate the effect of the temperature of H2 fire on structural steel and TR and ESD (riser) valves and if the installed PFP is sufficient	4 (no riser)
[13]	Do not use deluge on H2 fires because H2 release will become unignited and form a cloud: possible explosion (see hazard 1a)	4 (no deluge system)
[14]	Investigate additional training of personnel for H2 fire detection and fire fighting	1
[15]	Investigate the implications of high voltage installation on the platform with respect to interaction on humans, explosions and EM interferences and footprint on the platform	2 (see Section 3.1.4)
[16]	Consider storage of inventory of any drainage as injecting in the export line is not feasible	4 (no storage)
[17]	Investigate best location to vent O2 and keep in mind vessels, helicopter, escape pods, life boats etc.	3 (See Chapter 5)
[18]	Investigate blowdown scenarios	3 (See Chapter 6)
[19]	Investigate best location to vent H2 and keep in mind vessels, helicopter, escape pods etc.	3 (See Chapter 6)
[20]	Check if CO2 extinguishing on vent is still feasible	3 (See Chapter 6)
[21]	Check if design of vent piping has sufficient strength to withstand an explosion of H2	1
[22]	Check purging of vent to ensure no fire in vent piping	3 (See Chapter 6)
[23]	Perform radiation study on H2 vent	3 (See Chapter 6)
[24]	Investigate brine sampling. Continuous measurement of O2 concentration in H2 recommended. Ensure calibration points are placed such that it will not be a potential ignition source	1
[25]	Investigate that the start-up and shutdown procedure considers purging of the installation. Further this subject needs to be more specified when design is more mature	1
[26]	Ensure that gas detectors are modified to detect H2	4 (no gas detection)
[27]	Investigate if there will be a cable to shore, which means auxiliary power is not required	1
[28]	Investigate if instrument air is required for typical operations	1
[29]	Investigate if hydraulic systems are required for typical operations	4 (no hydraulic system)
[30]	Investigate if cooling water can be used to reduce typical air cooling hazards	4 (intrinsically safe)
[31]	Ensure PEM is stopped on losing cooling medium	4 (intrinsically safe)
[32]	Investigate how N2 is provided at the platform and ensure hazards associated with this installation are considered when design is more mature	4 (V_{N_2} very small)
[33]	No start-up without sufficient purging	4 (V_{N_2} very small)
[34]	Ensure sufficient buffer of N2 is available for safe shutdown of electrolyser	4 (V_{N_2} very small)
[35]	Ensure system (piping and equipment) is designed for these products	1
[36]	Investigate if pipeline is suitable (literature available)	1 (if new pipeline)
[37]	Investigate the operating philosophy of the biocide/anti-scalant injection to the desalination unit and associated hazards	1
[38]	Install adequate firefighting equipment on electrical equipment	1 (intrinsically safe)
[39]	Do not use fire extinguishing systems in case of H2 fire (potential of explosions)	4 (no active fire protection, see Section 3.1.6)
[40]	Relocate buffer vessel out of crane reach and/ or install sufficient protection	1
[41]	Provide sufficient lay-down areas outside any lifting areas from equipment at lower decks	1
[42]	Ensure PEM is located such that crane can reach the location taking into consideration favourable weather conditions and sea state	1
[43]	Vent study should also take into account corrosion on the installation	1

[44]	Ensure structure has sufficient strength for the intended lifetime	1
[45]	Ensure vessel is selected with sufficient dynamic positioning and minimize weight	1
[46]	All escape routes shall be reviewed since layout will change and also based on scenarios and radiation	1
[47]	Review if lifeboat can be lowered to sea, taking into consideration O2 vent	1
[48]	Ensure equipment can be maintained and reached by crane when required	1
[49]	Check area classification is suitable for H2	4

5 Consequence of continuous oxygen release

One of the main concerns that was mentioned in the HAZID performed in NSE3 is the continuous release of oxygen [11]. In ordinary conditions oxygen makes up 21% of air. Due to the continuous release the local concentration of oxygen will increase. The associated risks are: risk on human health, increased flammability, and degradation of materials. These concerns raised in NSE3 are the starting point for the analysis in this chapter. Figure 5.1 presents a schematic of the gas release scenarios calculated in this report. This chapter presents calculations on the release and dispersion of oxygen. Calculations on hydrogen releases are presented in Chapter 6.

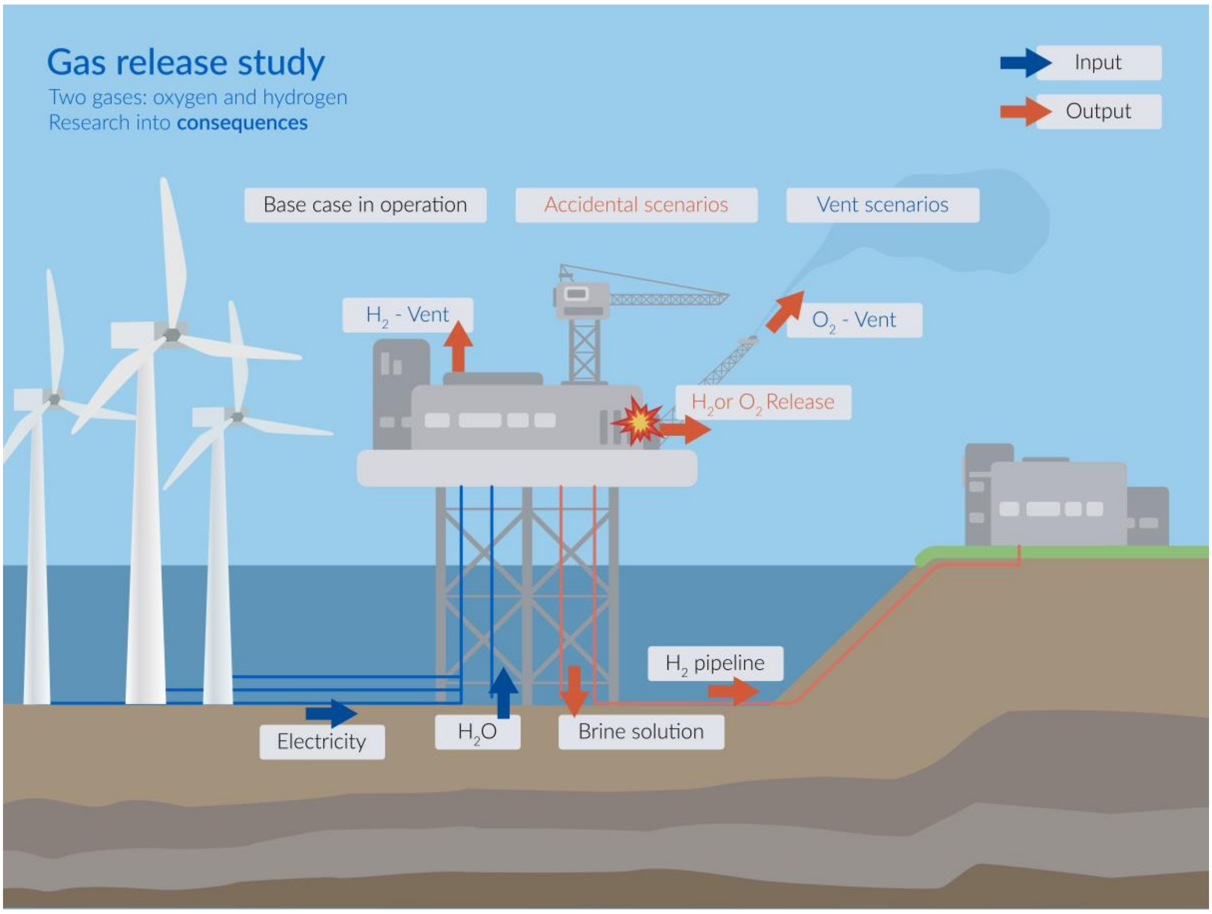


Figure 5.1 Gas release scenarios

5.1 Scenario definition

As the focus of NSE4 is mainly on a hydrogen generation platform, this is also the main topic of this chapter. However, a short section on oxygen venting on an hydrogen generation island is shown in section 5.5.

The envisioned power of the PEM electrolyser on a platform is 500 MW. With the assumption that 49 kWh results in 1 kg hydrogen and 8 kg oxygen, this results in large production flows of both hydrogen and oxygen: 1.2 10^5 Nm^3/h of hydrogen and 6.1 10^4 Nm^3/h of oxygen. The oxygen flow corresponds to 22.7 kg/s.

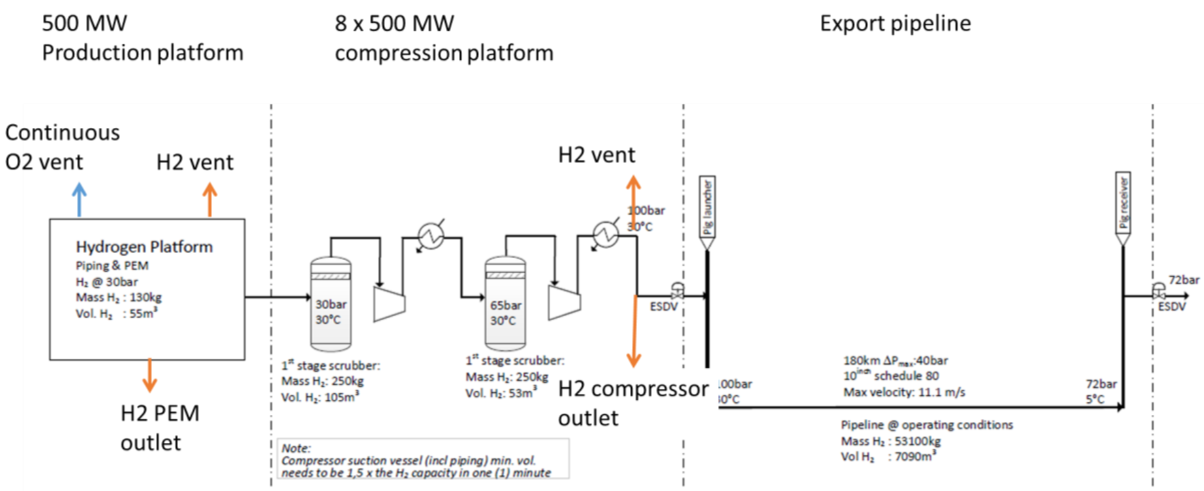


Figure 5.2 Simplified representation of relevant systems.

Figure 5.2 shows a simplified representation of the relevant components of the system on the platform. A more complete overview is given in by the process flow diagram in Appendix A . The PEM stack at the production platform is fed with electricity and water and produces hydrogen and oxygen at 30 barg. In the current chapter it is assumed that the oxygen is then vented into the atmosphere continuously. The hydrogen is transported to a separate compression platform and fed into a compressor to inject it into the export pipeline to shore. At the compression platform the hydrogen flow of eight production platforms are compressed for transport. No large-scale storage of hydrogen or oxygen on the platform is envisioned.

For this system a continuous oxygen release is planned. No oxygen is stored, all produced oxygen is directly vented into the atmosphere, i.e. the blue arrow in Figure 5.2. For oxygen also accidental releases can be defined, however, as storage and transport or shipping of oxygen are not considered in this chapter, these scenarios are not taken into account. In general the amount of oxygen released in an accidental release will not be larger than the amount released in the continuous scenario. Figure 5.2 also shows H_2 release scenarios, these will be discussed in Chapter 6.

Several design considerations can be given to decrease the risk of venting oxygen from an offshore platform. Oxygen could be pre-mixed with air before releasing it into the atmosphere, such that the oxygen concentration of the released gas is lower. Also, the oxygen could be heated, such that the temperature difference with the atmosphere is larger, resulting in a higher vertical velocity such that the cloud forms higher above the platform. Another idea could be to force the oxygen out, again increasing the vertical velocity. These design considerations are not regarded in the current study, but could be used to decrease the risk of venting oxygen. Other methods of offloading oxygen could be considered if abovementioned considerations do not suffice, such as transport via pipeline, ship, or a subsea release. These methods are not considered in this study.

5.2 Safety information oxygen

In ordinary conditions oxygen makes up 21% of air. Due to the continuous release the local concentration of oxygen will increase. The associated risks are: risk on human health, and increased flammability of materials. The combination of oxygen and hydrogen could lead to a highly explosive substance. However, the effect of the combined presence of oxygen and hydrogen is not considered in the dispersion scenarios. The outcome of the dispersion calculations could be used to design (the location of) the vent stacks of the two gases and the minimum distance between two 500MW hydrogen production platforms.

Risk on human health

According to the Dutch RIVM [26], the presence of oxygen can generally be omitted from risk assessments, unless large quantities are involved. In order to check the relevance of the presence of oxygen on the safety of people the following values can be used:

$p_{lethality}$=0.1 for oxygen concentration > 40%
$p_{lethality}$=0.01 for oxygen concentration between 30% and 40%
$p_{lethality}$=0 for oxygen concentration between 20% and 30%.

This means that for an oxygen concentration higher than 40%, there is a 10% probability that this concentration is lethal for humans.

Looking at the oxygen vent scenario, it is expected that such high concentrations of oxygen will only occur close to the venting location where no human presence is expected. The direct health risk of the venting of oxygen is minimum and can be neglected.

Risk on flammability

On the other hand, already smaller concentrations of oxygen give rise to higher risk of flammability. Fires will be more intense in higher oxygen concentration and material will more easily ignite. Already a small rise of concentration up to 23% of oxygen will increase the flammability risk [27]. For this reason, the concentration of 23% oxygen will be used to obtain contours for risk of increased flammability. As air already contains 21% of oxygen, the contour of interest in the dispersion calculations is 2.5% oxygen.

Risk on material degradation

Another risk of an increased concentration of oxygen is on corrosion control. It has been shown that an increase of the oxygen concentration results in an increase of the corrosion rate [28]. No data has been found in literature on the effect of an oxygen percentage higher than 21% on the corrosion rate, but data of different dissolved oxygen concentrations in water on the corrosion rate of carbon steel for pipelines (N80) are listed by Guangzhi et al. [28]. Guangzhi et al. found that the corrosion rate increases from 1.0 to 3.0 mm/year as the oxygen concentration in sea water increases from 10% to 20%. In offshore structures also a carbon structural steel is applied, but a coating needs to be applied for both the splash and atmospheric zone as determined in *DNVGL-OS-C101: Design of offshore steel structures, general – LRFD method*. Therefore, material degradation due to corrosion is reduced significantly in the structural steel. Nevertheless, the increased oxygen content should be included in corrosion control studies when designing the offshore hydrogen production platform steel structure.

5.3 Dispersion calculation set-up

For the continuous oxygen release, dispersion calculations are performed. The current section will focus on some aspects of the dispersion calculations that are common to all described scenarios.

5.3.1 Software for oxygen dispersion calculations: EFFECTS

For the release and dispersion calculations of oxygen the software EFFECTS (v11) [29] is used. This software combines several models for release and atmospheric dispersion. It can be used in complete Quantitative Risk Assessment (QRA) studies, however in this report only the consequence analysis is performed.

5.3.2 Atmospheric conditions

An important aspect of dispersion is the atmospheric stability, i.e. the amount of vertical motion in the atmosphere. In stable, misty conditions vertical motion is suppressed and mixing is limited. These conditions fall under stability class F, which means very stable. On a sunny day vertical motions in the atmosphere are present at a larger scale and mixing is more pronounced, this is stability class A, very unstable. With little solar heat influx during daytime, i.e. clouded weather, the atmosphere is called neutral: vertical motions are neither suppressed nor enhanced. This is stability class D.

For a QRA, six representative weather classes are to be used [30]. A choice from these conditions has been made for the current study, see Table 5.1. Only the neutral and stable conditions have been retained as these are expected to give the largest effect distances. On shore the stable atmospheric conditions will mostly give worst case results. However, at sea these stable conditions do not usually occur due to the smaller temperature differences between the sea water and air. [31] And stability class D1.5 is considered worst case. In the following analysis D1.5 will be used as the base case and the stable atmospheric conditions will only be used in the sensitivity analysis.

Table 5.1 Description of used weather classes. The letter gives the stability class, the number indicated the wind velocity in m/s at 10 m height.

Stability class	Description
D 1.5	Neutral atmospheric conditions, heavy overcast with low wind velocity
D 5	Neutral atmospheric conditions, heavy overcast with moderate wind velocity
D 9	Neutral atmospheric conditions, heavy overcast with high wind velocity
F 1.5	Stable atmospheric conditions, clear night with low wind velocity
F 2.0	Stable atmospheric conditions, clear night with low wind velocity

Note that the wind velocities are given at 10m above sea level. The turbines are located at 90 to 150 m above sea level, dependent on location and turbine type. At these heights the wind velocity will be higher than at 10 m height. Below a certain cut-in speed the turbine will not be able to generate electricity, this cut-in speed depends on turbine type. Typical values for cut-in speed are 2.5 m/s (at 150 m height) to 3.5 m/s.(at 90 m height). This roughly corresponds to a wind velocity at 10 m height of 2 m/s and 2.9 m/s, respectively [13]. These values are above the 1.5 m/s that will be used for the base case calculations. This means that the approach chosen is a conservative approach for electricity produced from wind energy close the location of the production platform; for other electricity sources (e.g. solar power, or wind power from other wind farms across the North Sea) the approach can be less conservative.

5.4 Continuous release of oxygen 500 MW platform

This paragraph presents the results of the continuous release scenario of oxygen dispersion calculations. First, the input parameters and results of the base case are discussed, and secondly a sensitivity study is performed for several variations on the input parameter on the base case. The base case equals the most realistic release case for the current platform design in the Hub West scenario in combination with conservative atmospheric conditions.

The continuous release of oxygen is modelled using three steps: (i) gas release from a vessel (outflow model), (ii) jet flow, and (iii) a neutral gas passive dispersion. The first model describes the outflow from a vessel through a pipe, resulting in a mass flow rate. This mass flow rate is input for the high velocity jet model. This dilutes the oxygen with air. When the velocity of the jet is reduced sufficiently, passive gas dispersion is started as the final step. At this point the density of the oxygen/air mixture is only slightly higher than the density of air, for this reason no buoyance effects are expected and a neutral dispersion model is used. A schematic representation of the used models is shown in Figure 5.3.

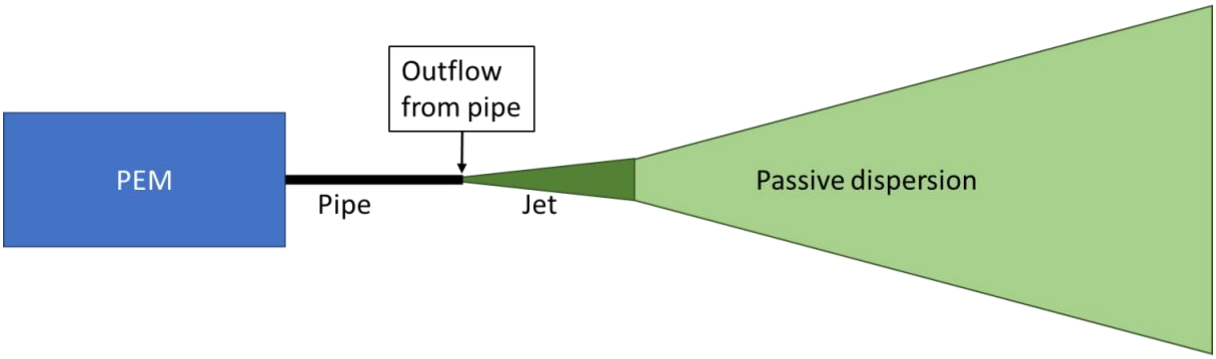


Figure 5.3 Schematic representation of used models for oxygen dispersion.

5.4.1 Base case

5.4.1.1 Input parameters base case

The input parameters for the base case calculation are given in Table 5.2. The base case parameters are taken from WP1 [13] when available. When unavailable, realistic estimations have been made. The parameters describe the process parameters, the release geometry, and the atmospheric conditions. The final parameter is the concentration averaging time. This is set at 20 s, the base value used for flammable substances used in the EFFECTS software.

Table 5.2 Input parameters for base case oxygen dispersion.

Parameter	Value
Pressure inside PEM	30 bar
Temperature inside PEM	45 °C
Mass flow rate oxygen	22.7 kg/s
Pipeline and outflow diameter	80 mm
Release height	30 m
Release direction	Vertical release
Atmospheric conditions	D1.5
Averaging time	20 sec

5.4.1.2 Results base case

The first step in the calculation is the release of the oxygen. At the exit of the pipeline, the pressure is higher than atmospheric and the oxygen is released with a high velocity jet. Away from the release point, the velocity decreases and becomes comparable to the atmospheric velocity. At this point the jet model is stopped. The results of the jet model are used as input for the passive dispersion model.

The concentration at the centre of the jet as a function of distance from the release point is shown in Figure 5.4. The initial jet consists completely of oxygen, therefore a concentration of 100 vol% is present at the outflow location. The concentration plotted in Figure 5.4 starts just above 200 vol%. This is due to the method of calculating the concentration. Internally EFFECTS uses mass based concentrations, when these are recalculated to volume concentrations, normal pressure and normal temperature are used. For high pressure, which will be present close to the outflow location, this will give rise to an overestimation of the volume fraction. After the expansion of the jet to a lower pressure, the volume percentage is correct.

The jet outflow reaches up to 37m (vertically) above the release point, i.e. with a release height of 30m above sea level this means 67m above sea level. At that point the maximum concentration at the centre line of the jet has been reduced to 3.6 vol%. This value is higher than the value of interest (2.5 vol%) and the calculation is continued with the dispersion model. At this point the density of the oxygen jet is 1.21 kg/m^3, which is very close to the atmospheric density. No buoyancy effects are expected and the neutral gas dispersion model can be used.

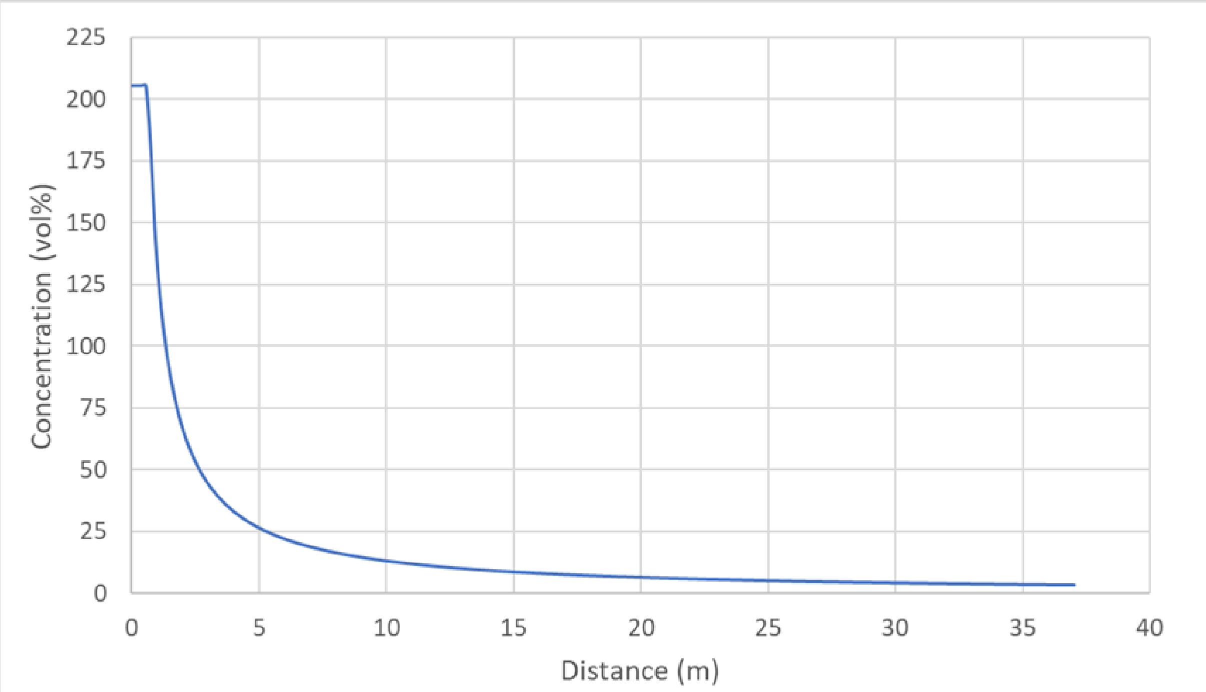


Figure 5.4 Concentration vs vertical distance to release point in oxygen jet.

The neutral gas dispersion model results in an oxygen plume. The concentration at the (horizontal) centre line of the plume as a function of distance is shown as the blue line in Figure 5.5. The orange horizontal line represents 3.6 vol% oxygen and the green horizontal line represents 2.5 vol% oxygen. Due to the inner workings of the used models the initial concentration at the cloud centre line starts at 8.5 vol%, which is significantly higher than the 3.6 vol% at which the jet was ended. After 39 m the concentration at the centre line is reduced to 2.5 vol%.

The difference between the 3.6 vol% as the end point of the jet model and the 8.5 vol% as the starting point of the dispersion model raised some questions. After consultation with the EFFECTS helpdesk an alternative approach has been adopted to determine the distance at which 2.5 vol% is reached. The distance in the plume between the location at which the concentration reaches 3.6 vol%, i.e. the concentration at the end point of the release model, and the location at which the concentration reaches 2.5 vol%, i.e. the concentration of interest, is taken as the effect distance. In Figure 5.5 this would be the distance between the intersection point of the orange line and the blue curve and the intersection point of the green line and the blue curve, i.e. the distance between the two dotted black vertical lines. For the base case this distance is 15 m. Ideally this approach should be validated, however, no literature on oxygen dispersion on this scale have been found.

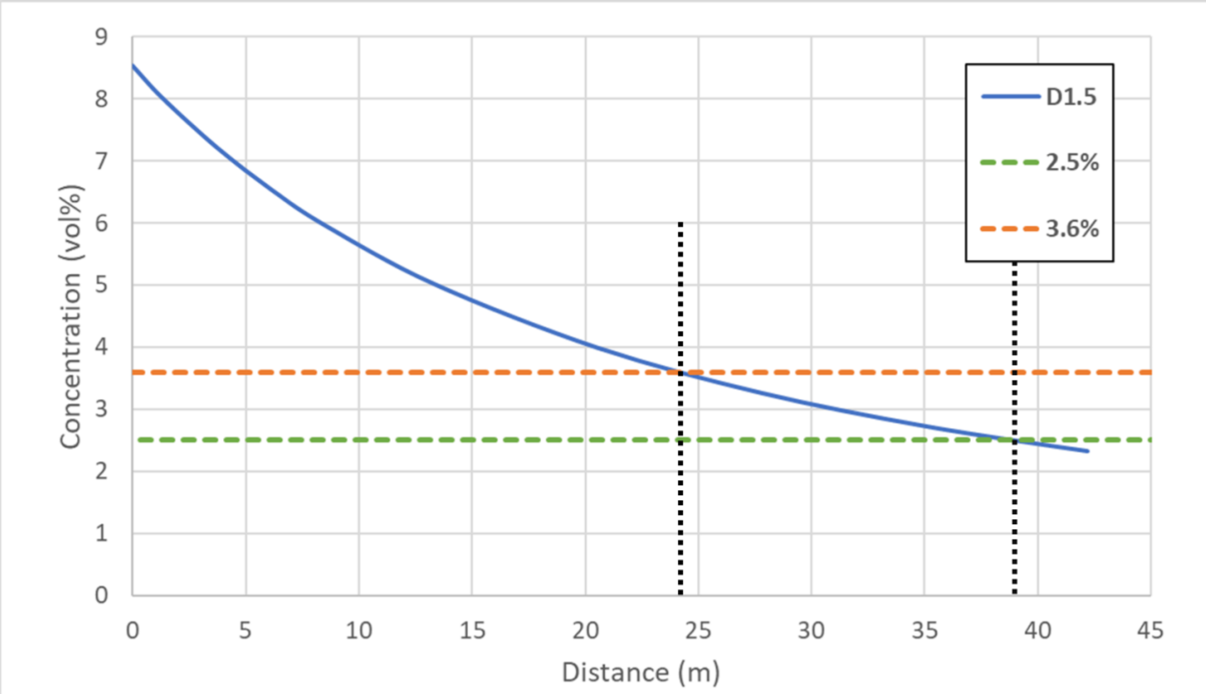


Figure 5.5 Concentration oxygen as function of distance. The orange and green horizontal lines represent 3.6 vol% and 2.5 vol% oxygen, respectively.

Therefore the maximum horizontal effect distance for the base case is 15m.

5.4.2 Sensitivity study

Using the base case as a starting point, several variations on the input parameters have been investigated. The investigated variations are shown in Table 5.3.

Table 5.3 Input for parameter study.

Parameter	Value variations	Section
Atmospheric conditions	D 1.5, 5.0, 9.0; F1.5, F2.0	5.4.2.1
Release angle	0°, 20°, 45°, 70°, 90°	5.4.2.2
Release height	0, 10, 20, 30, 40, 50, 60 m	5.4.2.3
Pressure	5, 10, 20, 30, 35, 40 bar	5.4.2.4
Release temperature	-5, 5, 15, 25, 35, 45 °C	5.4.2.5

5.4.2.1 Atmospheric conditions variation

Keeping all other parameters constant, the atmospheric conditions (wind velocity and stability) are varied: D 1.5, D 5.0, D 9.0, F 1.5, and F 2.0; i.e. 3 wind velocities for a neutral atmosphere and 2 wind conditions for a stable atmosphere.

The atmospheric condition only affects the passive dispersion model. The results of the release model and the jet model, i.e. end point of the release model at 67 m height with an end concentration of 3.6 vol%, remain the same. The starting concentration for the dispersion is set to 3.6 vol% using the procedure described in section 5.4.1.2. The resulting concentration versus distance is plotted in Figure 5.6. The two main observations are:

- concentration decreases faster if wind velocity is higher;
- concentration decreases faster for neutral atmosphere than for stable atmospheric conditions.
- The distances are reported in Table 5.4. For F1.5 no distance is reported, the jet reaches above the mixing layer height and the dispersion model is not valid in that situation.

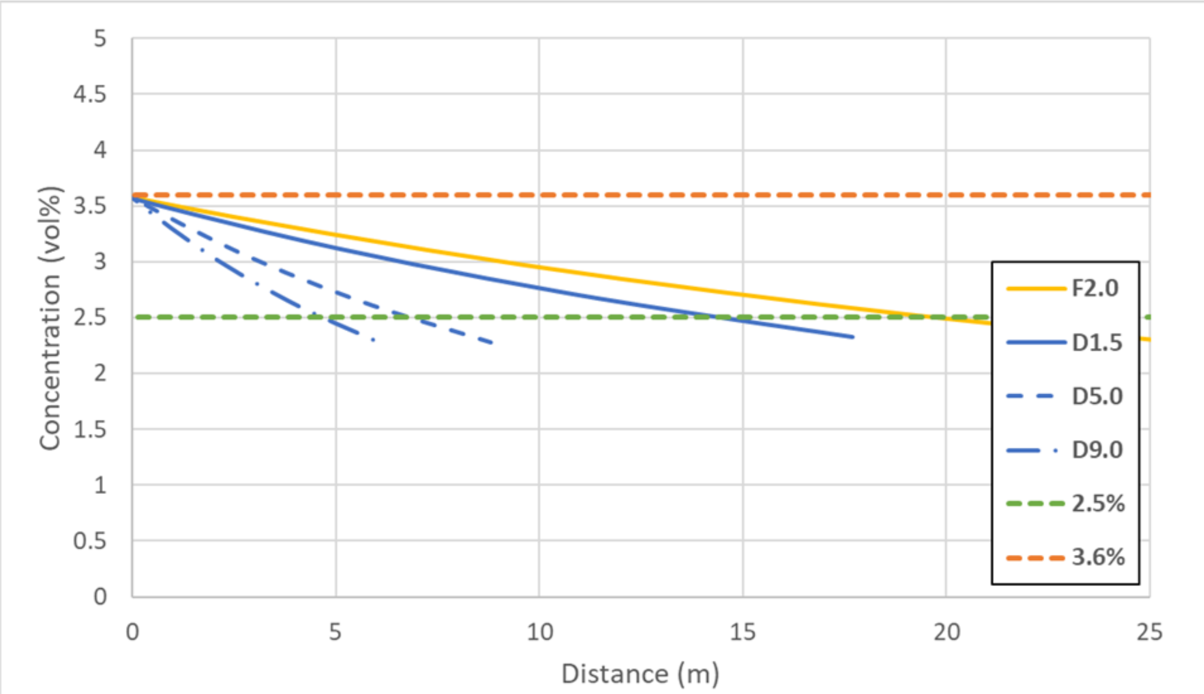


Figure 5.6 Concentration vs distance for varying atmospheric conditions.

Table 5.4 Horizonal effect distances for different atmospheric conditions.

Atmospheric condition	Effect distance (m)
F 1.5	-
F 2.0	20
D 1.5	15
D 5.0	7
D 9.0	5

5.4.2.2 Release angle variation

A second variation is the release direction. A vent line is typically oriented at 45° to transport the gases away from the platform. The actual release direction is mostly chosen to be vertical. In the current section the release direction is changed in several steps from vertical (90 degrees) to horizontal (0 degrees).

Figure 5.7 shows the cloud side view for the release angle variation. For all five cases the release and jet models are identical and stop at 37m from the release point. The only difference is the location of this end point. The concentration for the passive dispersion part is shown in Figure 5.8. The main contributor to the distance at which 2.5 vol% oxygen is reached is the release direction. The distances are reported in Table 5.5.

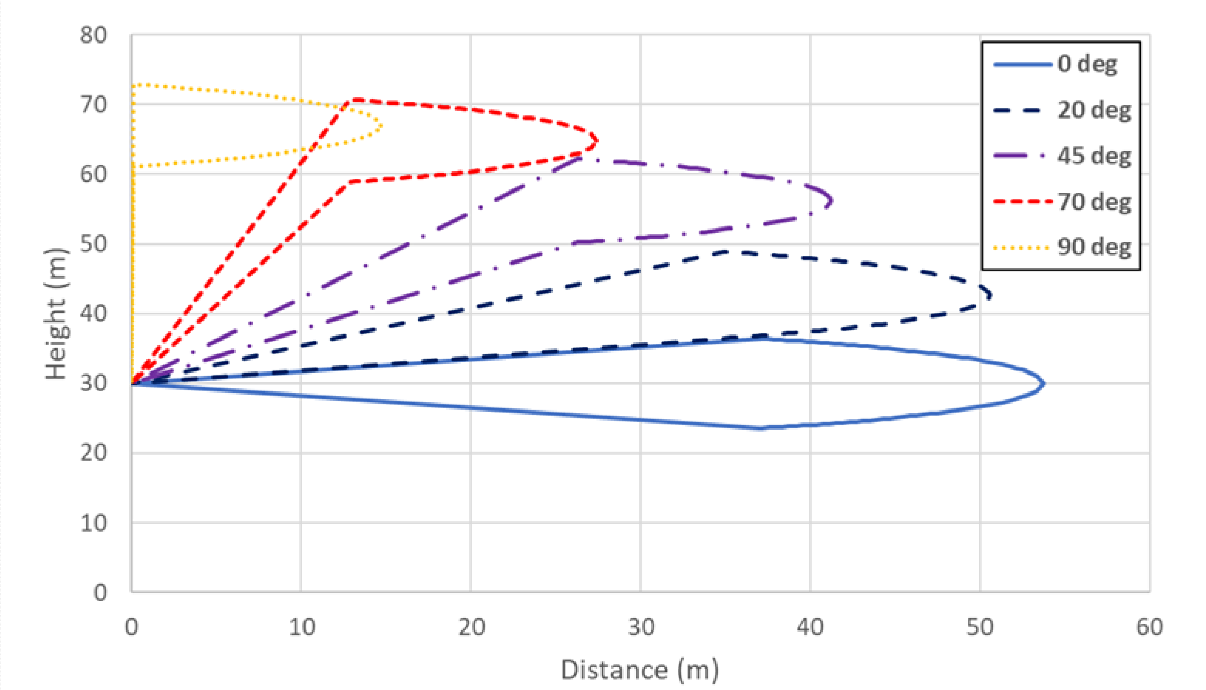


Figure 5.7 Cloud side view for various outflow directions.

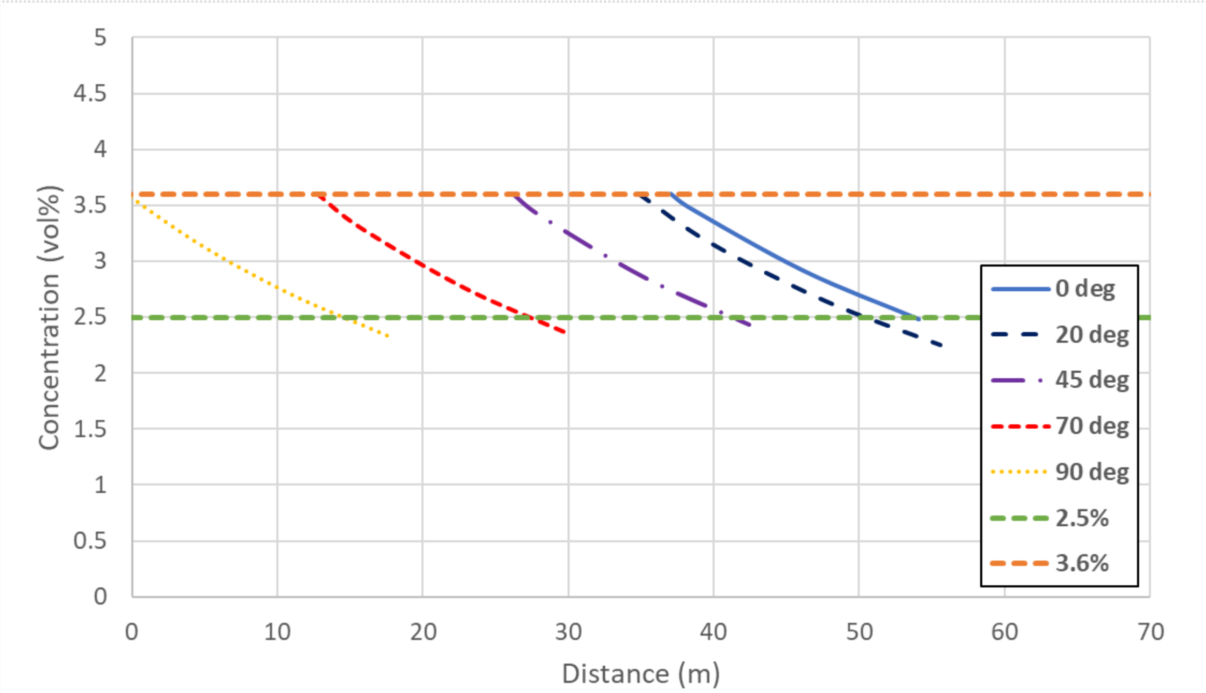


Figure 5.8 Concentration in dispersion model versus horizontal distance for various outflow directions ; horizontal: (0°) to vertical (90°). Lines start at horizontal distance of end point jet model.

Table 5.5 Effect distances for different outflow angles.

Angle	Vertical distance to endpoint release model	Horizontal distance to endpoint release model	Total horizontal effect distance (m)
0°	30	37	54
20°	43	35	51
45°	56	26	41
70°	65	13	27
90°	67	0	15

5.4.2.3 Release height variation

The third variation is the release height. This doesn't influence the length of the jet, or the concentration as a function of distance to the release point. This is due to the fact that the wind velocity as a function of height shows only a slow increase in height. However the difference in release height does effect the height of the end point of the jet model, see Table 5.6.

The concentration as a function of distance for varying release height is plotted in Figure 5.9. The horizontal distances at which the concentration is reduced to 2.5 vol% is relatively insensitive for the release height, the numbers are reported in Table 5.6.

The release height mainly influences the height of the centre of the cloud, which is clearly depicted in Figure 5.10, which shows the cloud side views.

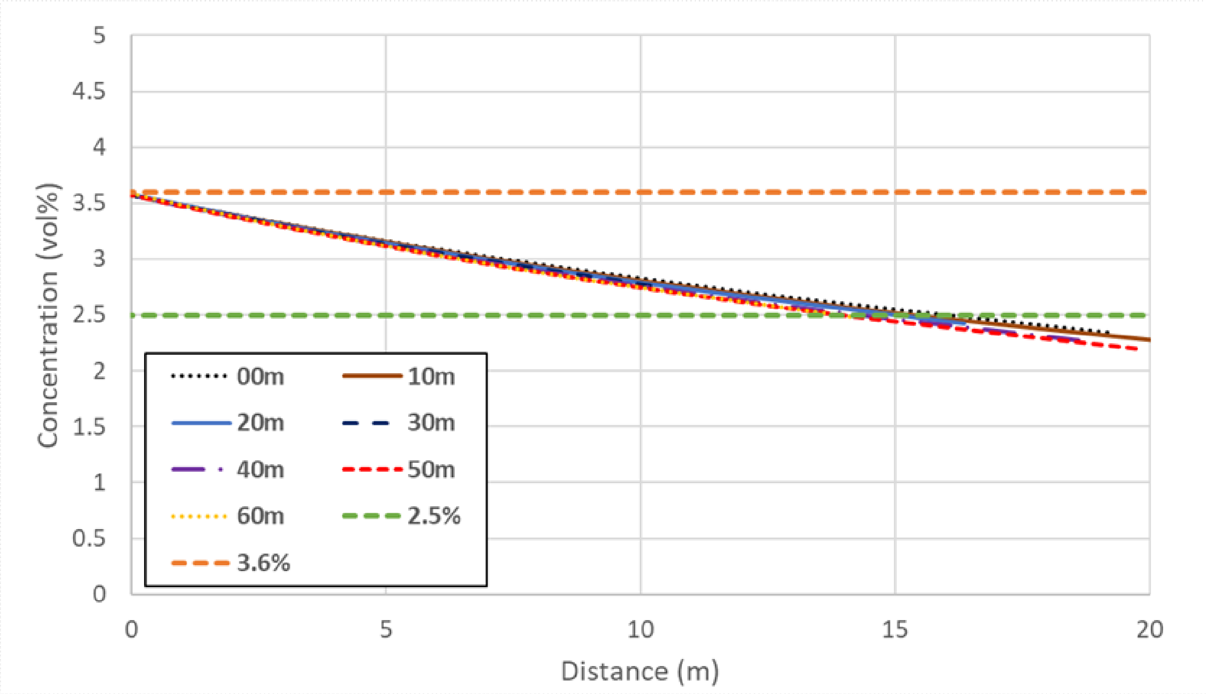


Figure 5.9 Concentration vs distance for varying release height.

Table 5.6 Effect distances for different outflow heights.

Release height (m)	Height of endpoint of release model (m)	Horizontal effect distance (m)
0	37	16
10	47	16
20	57	15
30	67	15
40	77	14
50	87	14
60	97	14

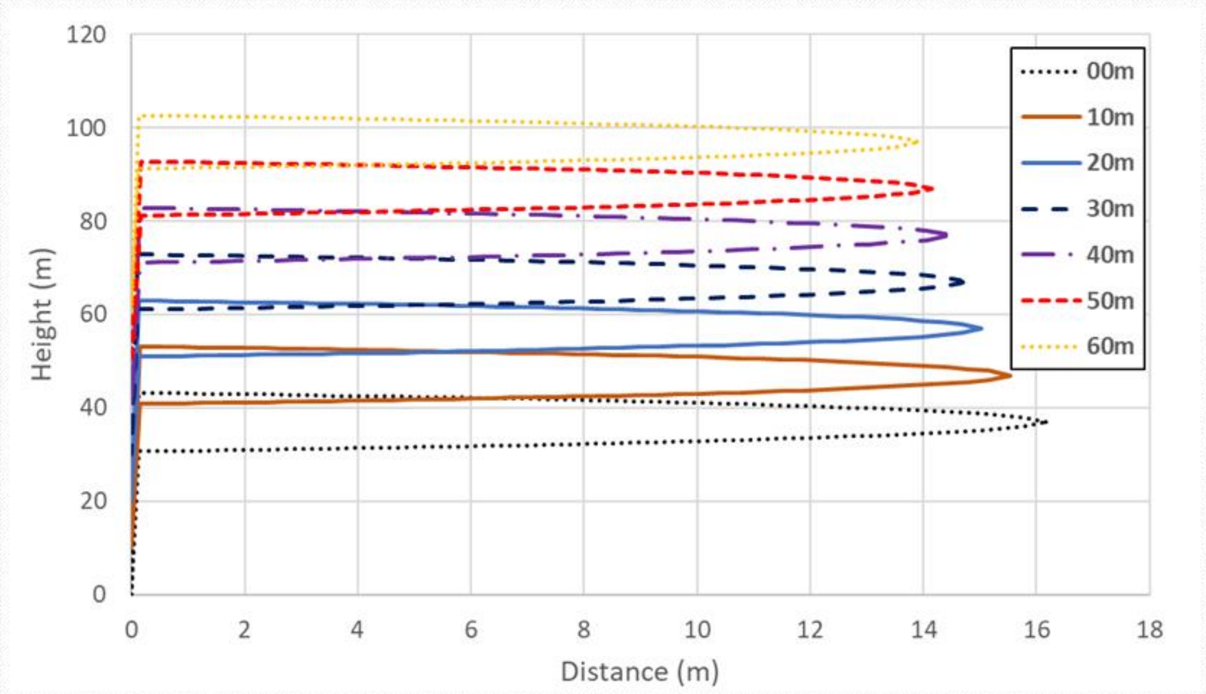


Figure 5.10 Cloud side view for various release heights.

5.4.2.4 PEM pressure variation

The base condition is an operating pressure of 30 bar for the PEM. Using the same pipeline lengths and diameter, the pressure inside the PEM has been varied. As the pressure and mass flow rate can't be set independently, a higher pressure results in a higher mass flow rate, in general a higher endpoint of the jet model and a higher O_2 concentration at this location, see Table 5.7. The resulting oxygen concentration in the dispersion model as a function of horizontal distance is shown in Figure 5.11. For these concentrations the correction described in section 5.4.1.2 has been used. The distances are reported in Table 5.7. For 5 and 10 bar, no results are reported. The concentration in the jet decrease to below 2.5% and no passive dispersion is calculated. Note that the outcomes of these calculation depend both on pressure and mass flow.

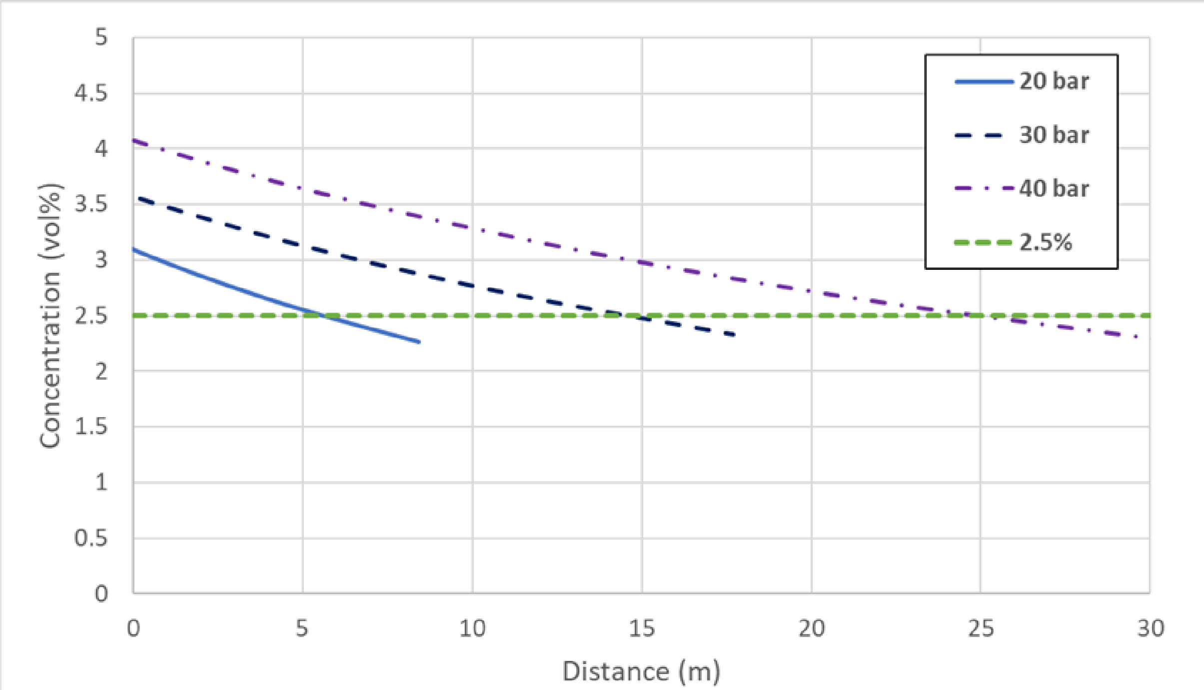


Figure 5.11 Concentration vs distance for varying PEM operating pressure.

Table 5.7 Effect distances for different initial pressures.

Pressure [bar] (Outflow rate [kg/s])	Height of endpoint of release model (m)	Concentration at endpoint of release model (vol%)	Horizontal effect distance (m)
5 (4)	64	1.6	NA
10 (8)	63	2.3	NA
20 (15)	65	3.1	6
30 (22.7)	67	3.6	15
40 (30)	69	4.1	25

5.4.2.5 Release temperature variation

From the vessel to the release point the pressure difference is 17 bar. Typically with this pressure drop also a decrease in temperature is expected. As a rule of thumb a change of pressure of ½ bar results in 1°C temperature change. This decrease in temperature is not visible in the base case calculation, where the temperature at the exit point of the pipe remains 45°C. In order to check the sensitivity for the temperature at the outflow location, the temperature at the start of the jet calculation has been manually changed to lower values, see Table 5.8. A lower temperature means a higher density and hence lower velocity. A pressure drop of 13 bar would give a temperature of 9°C at the exit of the vent line.

The concentration vs distance in the passive dispersion is plotted in Figure 5.12. Lower temperatures lead to larger distances. The numbers are reported in Table 5.8. The base case has an effect distance of 15 m, whereas a lower exit temperature of 5 °C has an effect distance or 27 m. As a temperature drop is to be expected at the exit, the distance of 27m is to be taken as the distance of interest in the design of the vent location.

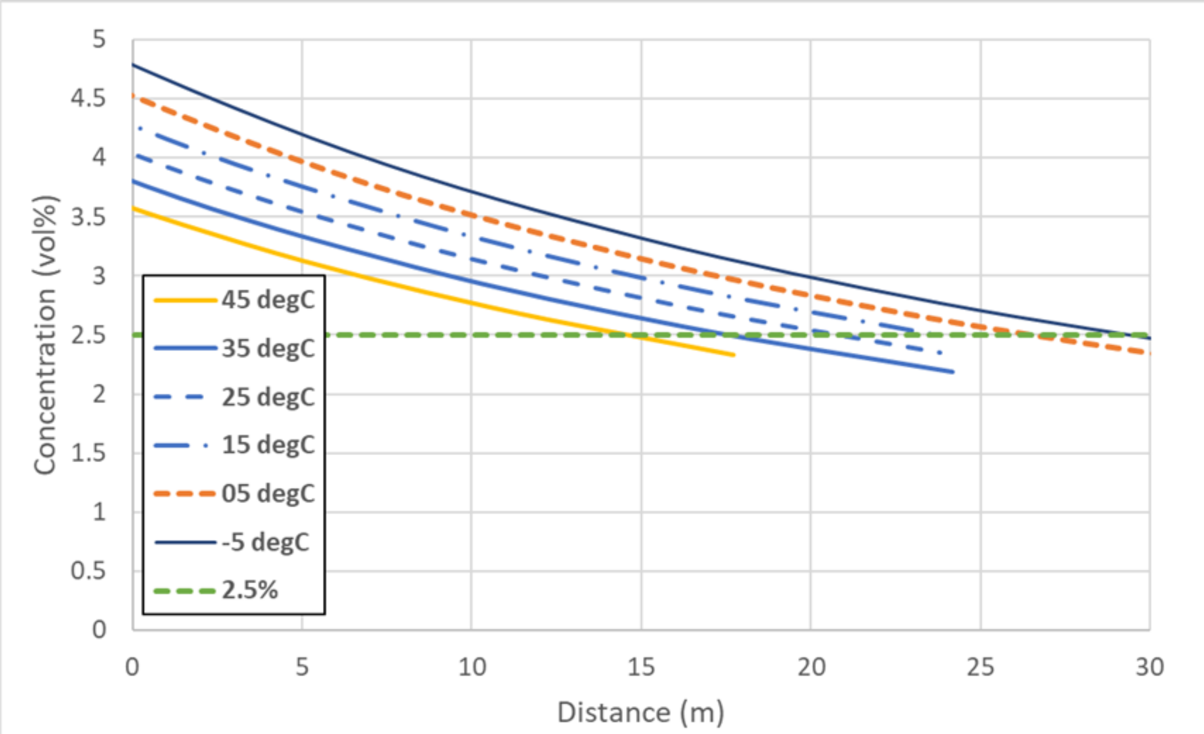


Figure 5.12 Concentration vs distance for changing outflow temperatures.

Table 5.8 Effect distances for different outflow temperatures.

Temperature at outflow (°C)	Height of end point jet model (m)	Concentration at end point of jet model (vol%)	Horizontal effect distance (m)
-5	30	4.8	30
5	31	4.5	27
15	33	4.3	24
25	34	4.0	21
35	36	3.8	18
45	37	3.6	15

5.4.3 Conclusions continuous oxygen release

In the previous subsections the oxygen concentration as a function of dispersion distance is shown for several variations on the base case. The base case gives a distance of 15 m at which the concentration of 2.5 vol% is reached. The results of the sensitivity study are summarised in Figure 5.13. The sensitivity study leads to the following conclusions:

- Increasing wind velocity results in smaller distances.
- Moving from a horizontal to a vertical release decreases the horizontal distance and increases the height of the centre of the cloud.
- Higher pressure with increasing mass flow rate results in larger horizontal distances.
- Release height has only a small effect on the horizontal distance.
- Lowering outflow temperature leads to a larger distance.

Another important outcome is the result that the released oxygen will have a density compared to air after mixing. This means that it will behave as a neutral gas and buoyancy effects are not important.

Taking into account an expected drop in temperature of the oxygen inside the piping a horizontal effect distance of 27 m and a vertical distance of 31 m should be considered when determining the location and the length of the vent pipe. There should be no interference between the oxygen cloud and the platform as this will increase the flammability risk. Note that the results shown in the current chapter are for 22.7 kg/s oxygen; for other mass flow rates a new calculation should be performed.

The used models are validated. Unfortunately no literature was found on oxygen release to validate the outcome of the calculations.

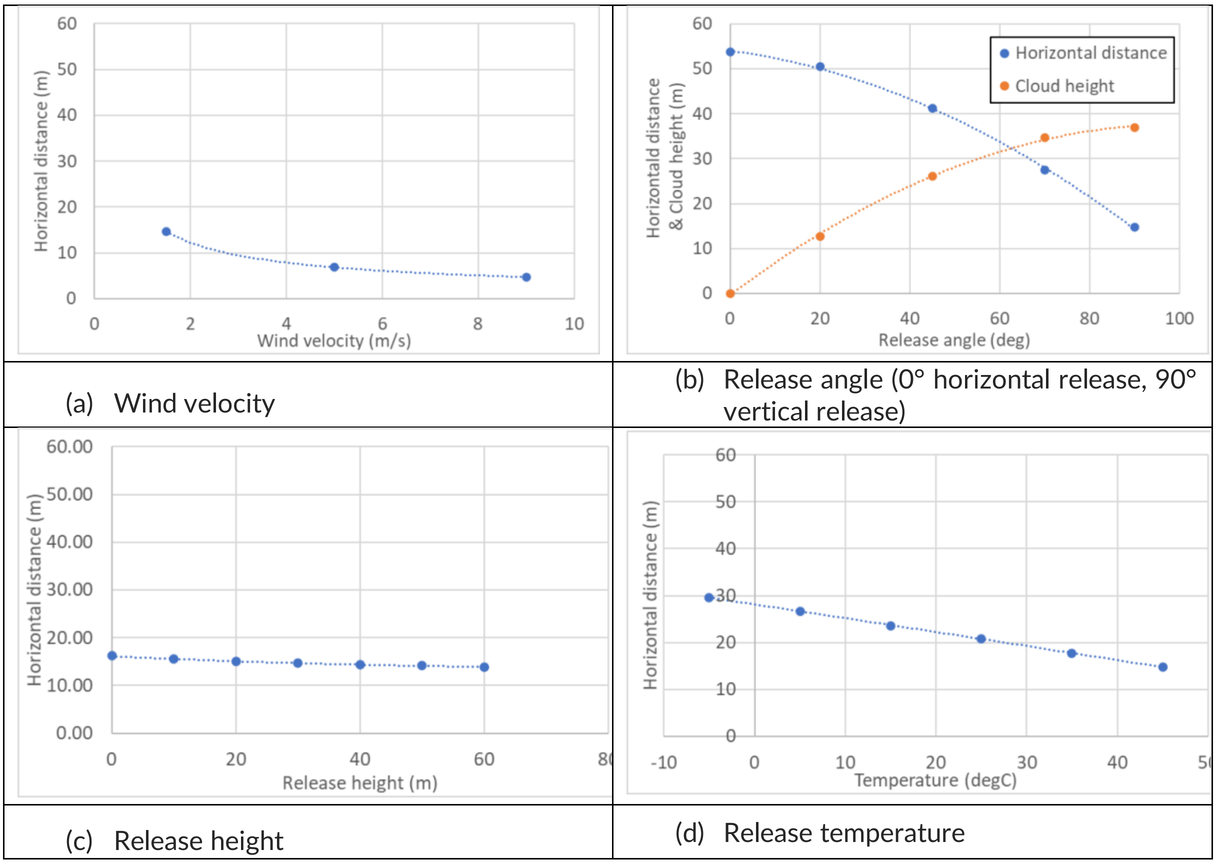


Figure 5.13 Overview of sensitivities.

5.5 Continuous release of oxygen 4 GW production island

5.5.1 Input parameters

One of the options for offshore H_2 production is the production on an artificial island. The dimension of the island design is 500mx500m [13]. At such a surface area a larger production capacity can be placed than on a platform. The design capacity for such an island is 4GW, i.e. 8 times larger than for a platform. The increased capacity will also lead to a higher flow of produces oxygen that (possibly) is to be vented. For this situation a vent study is performed.

The input parameters for this vent study are given in Table 5.9. Most parameter are identical to the platform case. The main difference in input parameters is the diameter of the vent line. Due to the increased mass flow rate (181 kg/s instead of 27 kg/s) an larger pipe diameter of 210 mm is taken. The temperature at the outflow location is varied between -5 °C and 45 °C.

Table 5.9 Input parameters for oxygen dispersion for 4GW production island.

Parameter	Value
Pressure inside PEM	30 bar
Temperature inside PEM	45 °C
Outflow temperature	-5, 5, 15, 25, 35, 45 °C
Mass flow rate oxygen	181 kg/s
Pipeline and outflow diameter	210 mm
Release height	33 m
Release direction	Vertical release
Atmospheric conditions	D1.5
Averaging time	20 sec

5.5.2 Results

The calculations result in distances at which the concentration of interest (2.5 vol%) is reached. The obtained distances are given in Figure 5.14 and Table 5.10. A higher outflow temperature results in a higher jet and a smaller effect distance. The concentration of 2.5 vol% doesn't reach the ground for all calculated plumes.

The higher mass flow rate when compared to the 500 MW production platform (Section 5.4) has several effects:

- the effect distance is larger: 142 m to 183 m for varying outflow temperature;
- the jet ends higher;
- and the concentration at the end of the jet is higher.

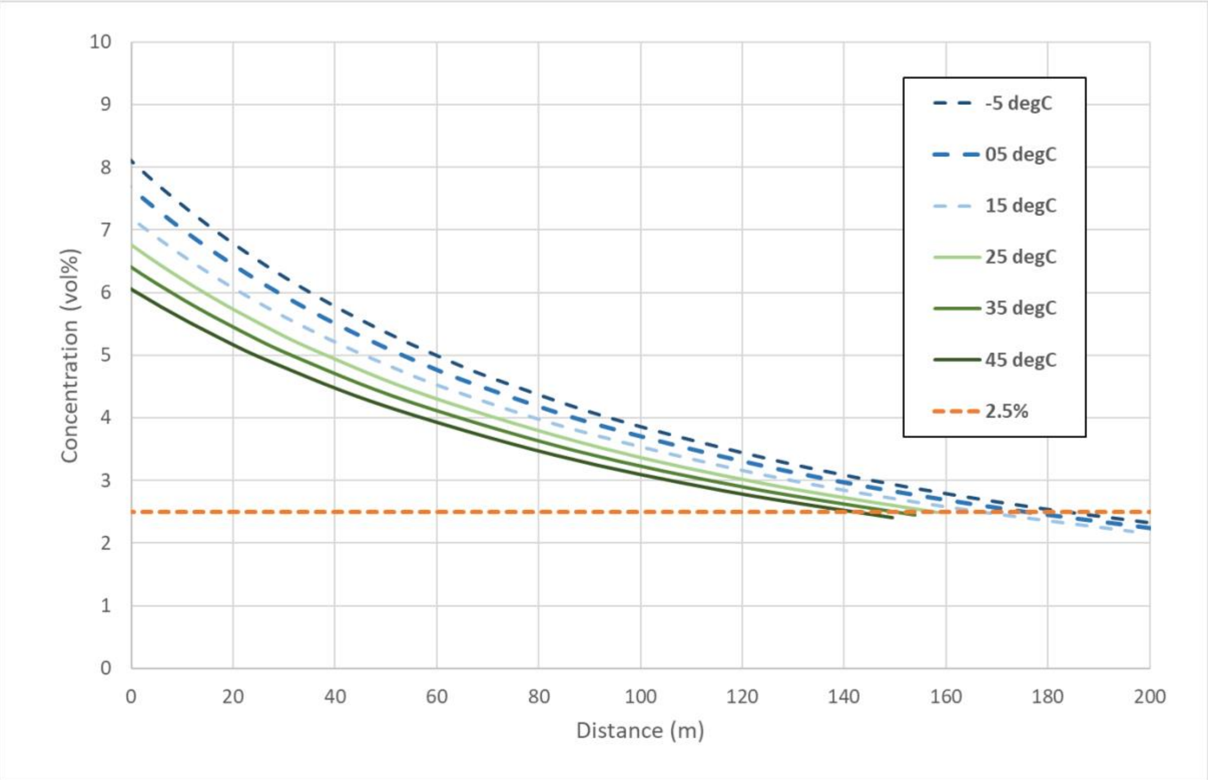


Figure 5.14 Concentration as a function of downwind distance.

Table 5.10 Effect distances 4 GW production island.

Temperature at outflow (°C)	Height of end point jet model (m)	Concentration at end point of jet model (vol%)	Horizontal effect distance (m)
-5	52	8.1	183
5	54	7.6	176
15	56	7.2	167
25	58	6.8	157
35	61	6.4	150
45	63	6.1	142

5.5.3 Conclusions continuous oxygen release

The obtained distances of 142-183 m are well within in the dimensions of the island. The obtained distance should be taken into account in the design of the island. The increase in effect distance is approximately linear with increasing mass flow rate.

If the effect area can't be accommodated, it might be an option to split the mass flow to separate vent stacks. For this situation the effect distances should be recalculated.

The effect distance can be reduced by heating the oxygen before release, this results in a higher outflow velocity, with higher mixing and lower concentrations. Another option would be to pre-mix the oxygen with air, reducing the oxygen concentration, increasing the mass flow and reducing the effect distances.

6 Consequence of hydrogen release

Next to the continuous release of oxygen, one of the concerns that was mentioned in the HAZID performed in NSE3 is the release of hydrogen gas [11]. Hydrogen gas will be in an enclosed system on a hydrogen production platform, but it can be that it needs to be vented to prevent over-pressure or an accident can result in a hydrogen release. Hydrogen is a highly explosive gas, which means that it requires a relative small amount of energy to ignite. Therefore it is of importance to know how the gas will behave. Figure 6.1 presents a schematic of the gas release scenarios calculated in this report. This chapter presents calculations on the release and dispersion of hydrogen.

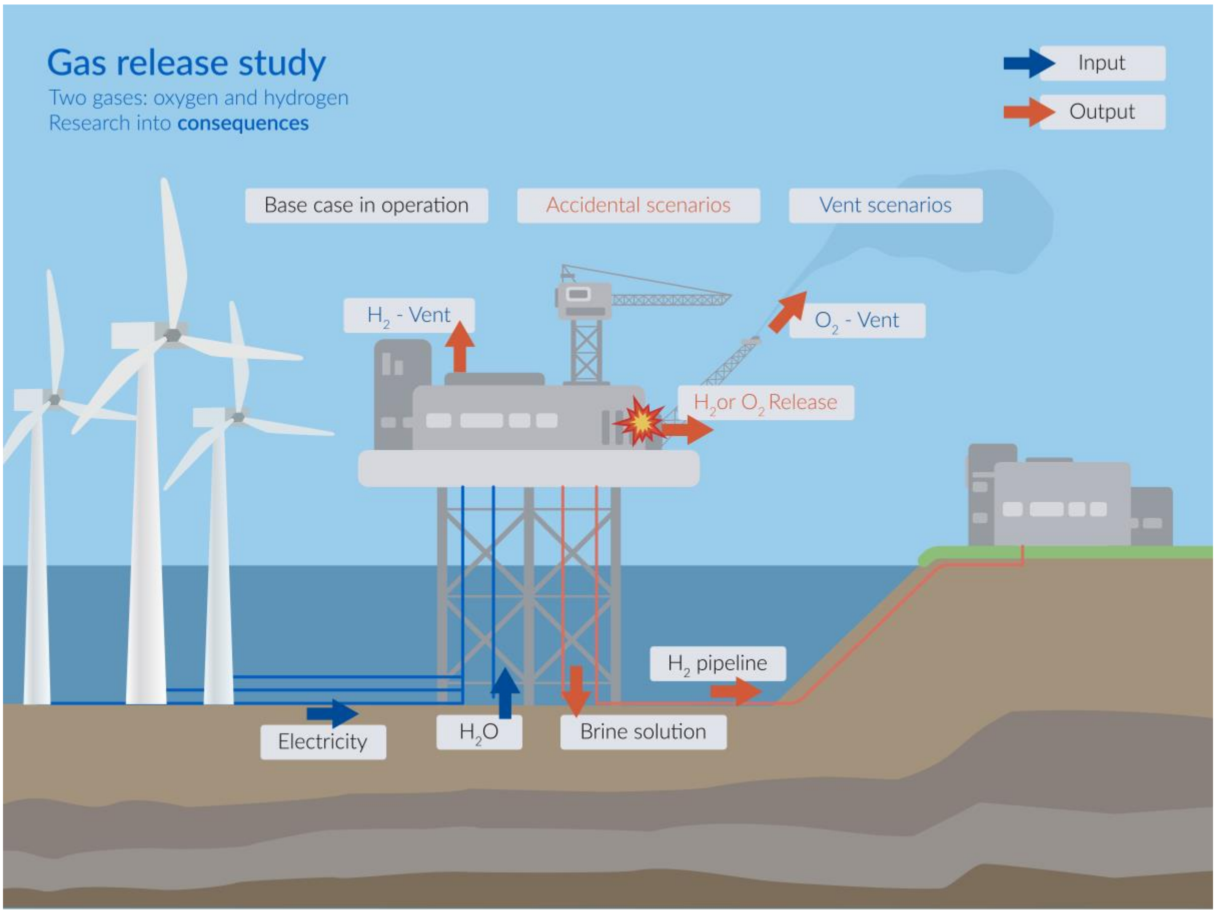


Figure 6.1 Gas release scenarios

6.1 Safety information hydrogen

Hydrogen is a lighter than air gas. When released, it will move upwards due to buoyancy effects. It also is a highly flammable gas. When hydrogen is released it can either ignite directly upon release leading to a jet fire, or a delayed ignition may occur that will lead to a cloud fire and in obstructed areas to an explosion.

6.2 Dispersion calculation set-up

6.2.1 Used software- PHAST

EFFECTS is (at the moment of writing) not validated for hydrogen dispersion calculations. The buoyancy behaviour of hydrogen is not captured correctly in the current version of the software (v11). Therefore, the calculations below were performed using PHAST software version 8.4.

6.2.2 Scenario description

The release scenarios for both oxygen and hydrogen are shown in Figure 5.2. The hydrogen is produced at a production platform which has a 500 MW capacity. The produced hydrogen of eight separate production platforms is transported to a single compression platform where the hydrogen is prepared for export through the export pipeline.

In total four release scenarios are studied. Two scenarios are located at the production platform: accidental hydrogen release from the PEM electrolyser (scenario 1) and hydrogen vent (scenario 2). The other two scenarios are located at the compression platform looking at the accidental release just after the hydrogen compressor (scenario 3) and a release at the hydrogen vent (scenario 4). The input numbers for the PHAST calculations for each of these scenarios are given in Table 6.1.

Table 6.1 Input numbers for hydrogen release scenarios.

Scenario N°		1	2	3	4
Description		H2 PEM Electrolyzer Outlet	H2 Vent (PEM platform)	H2 Export compressor Outlet	H2 Vent (Compressor platform)
Temperature	°C	30	30	30	30
Pressure	barg	30	30	100	100
Operating flow rate	kg/s	2.83	2.83	22.64	22.64
Release configuration		Horizontal (impacted & un-impacted) Vertical	Vertical	Horizontal (impacted & un-impacted) Vertical	Vertical
Release height	m	20	50	20	50
Inventory	kg	130	130	4000	4000
Line internal diameter	mm	457 (18”)	80	762 (30”)	80

6.2.3 Releases sizes and thresholds of interest

For each of the accidental scenarios (scenarios 1 and 3) the releases sizes and thresholds of interest are based on [26] and summarised in Table 6.2. The concentration of interest for an unignited is the lower flammability level (LFL) which is 4 vol% hydrogen (see Table 3.1). For an ignited release, the thermal radiation is regarded as threshold based on BEVI [26] .

Table 6.2 Release sizes and thresholds for scenarios 1 and 3.

Accidental release thresholds of interest		Hole sizes
Thermal radiation (kW/m²)	10	10% of ID
LFL (%)	4	10% of ID
Thermal radiation (kW/m²)	10	Full bore

LFL (%)	4	Full bore

For the releases associated to venting (scenarios 2 and 4), the following thresholds based on the API STD 521 [32] are considered and summarised in Table 6.3.

Table 6.3 Vents thresholds of interest.

Vent thresholds of interest		Release size
Thermal radiation (kW/m²) – Based on API STD 521	4,7	Vent diameter
LFL (%)	4	Vent diameter

6.2.4 Assumptions & atmospheric conditions

The assumptions and atmospheric conditions considered are reported in Table 6.4 and Table 6.5.

Table 6.4 Assumptions.

Assumptions
Flow composition is 100% H2
Time to isolation 600s

Table 6.5 Environmental conditions.

Environmental conditions	
Weather conditions	F2 -D1.5 - D5 - D9
Atmospheric & Surface temperature	9.85°C
Humidity	70%
Solar radiation flux	1 kw/m²

6.3 Results hydrogen releases

6.3.1 Scenario 1 – Production platform accidental release

6.3.1.1 10% ID release

The first situation at the production platform is an accidental release through a hole with a diameter of 10% of the pipe diameter. For this situation a stable release rate of 2.72 kg/s over a 600 seconds release duration is reached. This release is modelled either as a horizontal unignited release, a vertical unignited release or a horizontal jet fire. The calculation has been performed for four atmospheric conditions. For the first two release modes the furthest distance at which the LFL is reached is reported in Table 6.6. For the jet fire the furthest horizontal distance at which a heat flux level of 10 kW/m^2 is reached is reported, see Table 6.6. The furthest distances are found for D1.5 as the atmospheric condition.

Table 6.6 Scenario 1 - 10% ID release results.

46 mm release - Impact Distances (m)							
Scenarios			F2	D1.5	D5	D9	**Max**
Unignited release	Hor.	LFL	46	53	46	42	**53**
Unignited release (upward dist.)	Ver.	LFL	23	30	17	12	**30**
Jet fire	Hor.	10 kW/m2	29	29	28	27	**29**

6.3.1.2 Full bore release

For the full bore release scenario a peak release rate of 269 kg/s is found. This value can't be sustained for a longer period of time and is therefore discarded as input parameter. On a conservative approach, the total mass in the inventory (130 kg) is assumed to be released in 20s. This value is added to the production mass flow rate of 2.83 kg/s which results in an average leak release rate of 9.33 kg/s (6.5 kg/s + 2.83 kg/s) for the calculations. The impact distances for a horizontal release, a vertical release and a jet fire are reported in Table 6.7.

Table 6.7 Scenario 1 – Full bore release results.

Full bore release - Impact Distances (m)							
Scenarios			F2	D1.5	D5	D9	**Max**
Unignited release	Hor.	LFL	80	93	80	72	**93**
Unignited release (upward dist.)	Ver.	LFL	39	55	30	22	**55**
Jet fire	Hor.	10 kW/m2	51	51	51	50	**51**

6.3.1.3 Scenario 1 – Results summary

The impact distances for the accidental release (10% ID and full bore) are summarised in Table 6.8. These values are based on worst case scenarios. If these distances are deemed too large, the design of the platform should be updated with the placement of ESD valves to split the inventory etc. Afterwards the impact distances should be recalculated.

Table 6.8 Summary of results for scenario 1.

	46 mm hole size (10% of ID)	457 mm hole size (Full bore)
LFL maximum horizontal distance (m)	53	93
LFL maximum vertical distance (m)	30	55
10 kW/m² radiation maximum horizontal distance (m)	29	51

6.3.2 Scenario 2 – Production platform vent dispersion

The second scenario is the dispersion of vented hydrogen on the production platform. The input parameters for this calculation are shown in Table 6.9.

Table 6.9 Scenario 2 – Hydrogen vent input data PEM platform.

Stream Description		
Temperature	°C	30
Pressure	barg	30
Line internal diameter	mm	80
Pipe length	m	26
Components		
Hydrogen	%-Mole	100%
Source term		
Release rate	kg/s	3.2

Based on the mentioned assumptions, the LFL associated to the hydrogen released at the vent was found to reach a maximum horizontal distance of 10 m and a maximum vertical distance of 38 m from the release point, see Table 6.10.

This information is relevant for the positioning of both the hydrogen and the oxygen vents at the platform.

For the ignited release of hydrogen at the vent, the relevant result is the distance at which the heat flux is below 4.7 kW/m². It is found that no radiation effects above 4.7 kW/m² are reached at 15 m below the release point. This gives an indication for the required minimum height of the vent above the platform.

Table 6.10 Scenario 2 – Vent dispersion results.

Vent release - Impact Distances (m)							
Scenarios			F2	D1.5	D5	D9	**Max**
Unignited release (horizontal distance)	Ver.	LFL	7	7	9	10	**10**
Unignited release (upward distance)	Ver.	LFL	25	38	21	15	**38**
Ignited release - 15 m below release point	-	4.7 kW/m2	N.R.	N.R.	N.R.	N.R.	**N.R.**

*N.R. Not Reached

6.3.3 Scenario 3 – Compression platform accidental release

6.3.3.1 10% ID release

For the compression platform the amount of hydrogen and the pipeline diameter are larger, for this reason also the release rate used for the calculations is higher than for the production platform: 23.93 kg/s over a 600 seconds release duration. This value is only slightly higher than the operational flow rate and can be sustained over a longer time period.

The resulting distances for LFL and heat flux are reported in Table 6.11.

Table 6.11 Scenario 3 - 10% ID release results.

76 mm release - Impact Distances (m)							
Scenarios			F2	D1.5	D5	D9	**Max**
Unignited release	Hor.	LFL	115	134	115	103	**134**
Unignited release (upward dist.)	Ver.	LFL	85	57	47	34	**57**
Jet fire	Hor.	10 kW/m2	80	80	80	80	**80**

6.3.3.2 Full bore release

For the full bore release scenario a peak release rate of 2405 kg/s is found. This value can't be sustained for a longer period of time and is therefore discarded as input parameter. On a conservative approach, the total mass in the inventory (4000 kg) is assumed to be released in 20s. This value is added to the production mass flow rate of 22.83 kg/s which results in an average leak release rate of 222.83 kg/s (200 kg/s + 22.83 kg/s) for the calculations. The impact distances for a horizontal release, a vertical release and a jet fire are reported in Table 6.7.

Table 6.11 Scenario 3 – Full bore release results.

Full bore release - Impact Distances (m)							
Scenarios			F2	D1.5	D5	D9	**Max**
Unignited release	Hor.	LFL	283	328	290	259	**328**
Unignited release (upward dist.)	Ver.	LFL	115	248	135	98	**248**
Jet fire	Hor.	10 kW/m2	229	229	232	235	**235**

6.3.3.3 Scenario 3 – Results summary

The impact distances for the accidental release (10% ID and full bore) at the compressor platform are summarised in Table 6.12. Note that for these large amounts of hydrogen being released the distances remain smaller than the marine exclusion zone (500 m). Note that a conservative approach has been taken. The reported distances can be considered worst case numbers for this design. Placement of ESD valves at strategic location will reduce these distances.

Table 6.12 Summary of results for scenario 3.

	76 mm hole size (10% of ID)	762 mm hole size (Full bore)
LFL maximum horizontal distance (m)	134	328
LFL maximum vertical distance (m)	57	248
10 kW/m² radiation maximum horizontal distance (m)	80	235

6.3.4 Scenario 4 – Compressor platform vent dispersion

The fourth scenario is the dispersion of vented hydrogen on the compressor platform. The input parameters for this calculation are shown in Table 6.13.

Table 6.13 Scenario 4 – Hydrogen vent input data compressor platform.

Stream Description		
Temperature	°C	30
Pressure	barg	100
Line internal diameter	mm	80
Pipe length	m	26
Components		
Hydrogen	%-Mole	100%
Source term		
Release rate	kg/s	15.28

Based on the mentioned assumptions, the LFL associated to the hydrogen released at the vent was found to reach a maximum horizontal distance of 17 m and a maximum vertical distance of 67 m from the release point, see Table 6.14. This information is relevant for the positioning of both the hydrogen and the oxygen vent.

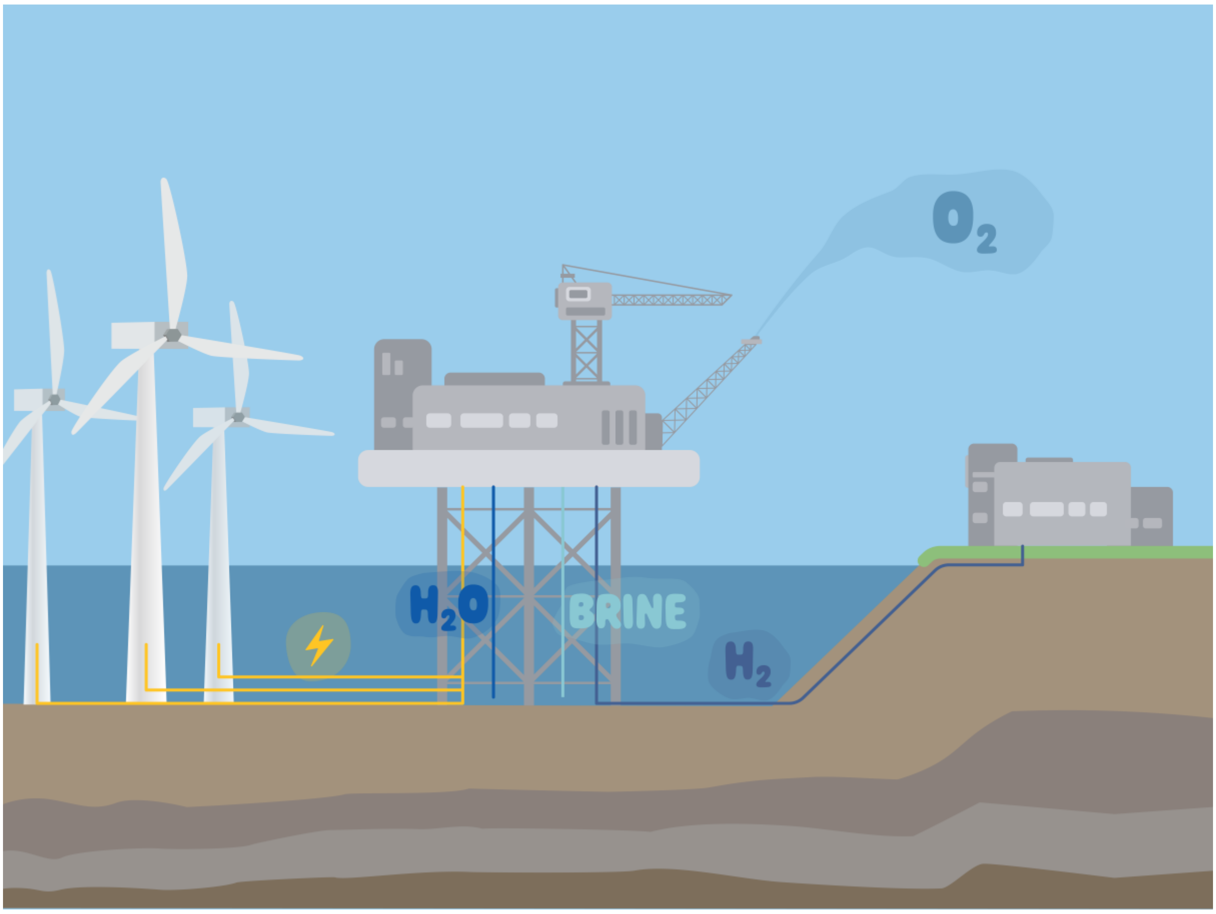
For the ignited release of hydrogen at the vent, the relevant result is the distance at which the heat flux is below 4.7 kW/m². It is found that no radiation effects above 4.7 kW/m² are reached at 20 m below the release point. This gives an indication for the required height of the vent above the platform.

Table 6.14 Scenario 4 – Vent dispersion results

Vent release - Impact Distances (m)							
Scenarios			F2	D1.5	D5	D9	**Max**
Unignited release (horizontal distance)	Ver.	LFL	13	12	15	17	**17**
Unignited release (upward distance)	Ver.	LFL	43	67	36	27	**67**
Ignited release - 20 m below release point	-	4.7 kW/m2	N.R.	N.R.	N.R.	N.R.	**N.R.**

*N.R.: Not Reached

6.4 Conclusions hydrogen releases



Hydrogen dispersion calculations were performed using PHAST v8.4 for accidental releases and vents releases for the electrolyser and the compression platforms with a conservative approach at an early design stage. None of the accidental releases were found to have dispersion or jet fire radiation impacts beyond the 500 m marine exclusion zone for both the electrolyser and compression platforms. Most effect distances of the accidental scenarios are larger than the platform size. To determine whether this consequence is acceptable, a risk assessment should be performed including probabilities of these scenarios.

The distances and heights found for the hydrogen venting scenarios can be used in the design process for determining the location and height of the vent stacks.

The distances obtained for the accidental releases can be reduced by the placement of ESD valves. If the platform design is updated with these measures, the impact distance calculation should be repeated.

7 Discussion

This chapter provides a discussion based on the results from Chapter 3, 5, and 6. The discussion is mainly focussed on the outcome of the consequence analysis for oxygen and hydrogen releases (Chapter 5 and 6).

7.1 Safety and integrity assessment

Chapter 3 provides lists of all systems on a platform for production of hydrogen which are changed compared to an offshore natural gas production platform. Two visuals are presented which include these systems and the links between them, one for a newly build platform, and one for a platform where the foundation structure of an existing platform is re-used. The systems are divided into different categories using safety and environmental critical elements. The visuals can be used when reviewing or developing standards to determine if all systems are covered in standards, or in pre-liminary designs to check if all systems have been regarded. The results do not provide guidelines on how to design a hydrogen production platform and the systems which should be regarded in the design are not limited to the given systems. No risk assessments are provided. The study tried to summarize both knowledge on design of natural gas platforms as knowledge on the safety considerations of hydrogen production systems. Since hydrogen production platforms on this scale are not (detailed) designed or fabricated yet, and knowledge on safety risks and considerations of systems often comes from experience, it is possible that some safety considerations change in time when man is more acquainted with large scale hydrogen production facilities.

7.2 Consequence analysis

Chapter 5 and 6 provide a consequence analysis on the release of oxygen and hydrogen gas respectively.

Oxygen release

The oxygen release consequence analysis presents effect distances for a continuous venting scenario for the 500 MW hydrogen production platform and 4 GW hydrogen production island. It is found that the risk of an increased flammability of materials results in the limiting oxygen concentration. A sensitivity study is performed for different environmental conditions, release angles, release heights, output pressures and output temperatures. The platform base case that corresponds to the platform design of WP1, results in a horizontal effect distance of 27 m and a vertical distance of 31 m. These distances can be incorporated in the design such that there is no increased flammability risk of materials on the hydrogen production platform. The island base case that corresponds to the island design of WP1, results in a horizontal effect distance of 176 m and a vertical distance of 54 m. The resulting cloud could therefore reach up to (approximately) 40% of the island length if the vent is located on the island. It should be further investigated whether this is workable, since in this area, no humans or flammable materials may be present. A solution could be to locate the vent outside of the island. Another important outcome is the result that the released oxygen will have a density compared to air after mixing. This means that it will behave as a neutral gas and buoyancy effects are not important.

Several assumptions have been made to get to these results, on which some discussion is possible.

- Mass flow rate based on an unconservative electrolyser efficiency.
- Continuous maximum capacity is given only. When electricity comes from wind parks, the mass flow rate and environmental condition are linked. A maximum capacity of 500MW will probably be linked to a larger wind speed than taken into account in the base case, resulting in smaller effect distances.

Also, wind turbines do not generate electricity below a cut-in wind speed. These correspond to a wind speed of minimum 2 m/s at 10 m height. In the base case a wind speed of 1.5 m/s is assumed, which is therefore a conservative approach. For other electricity sources (e.g. solar power, or wind power from other wind farms across the North Sea) the approach can be less conservative.

- It is assumed that in the second step of the model (jet flow), the wind velocity does not affect the flow of the oxygen. The wind velocity only has an effect on the effect distance in the third step (neutral gas passive dispersion), where the velocity of the flow has been reduced sufficiently. Due to this modelling assumption, the horizontal effect distance decreases for a larger wind speed. However, it could be that by taking the wind velocity into account in the jet flow, that this relation is reversed.
- The used models are validated for oxygen gas, however the coupling of the models is not. The outcome of the combination of these models is not validated, since no literature is available.

Hydrogen release

The hydrogen release consequence analysis presents effect distances for both venting as accidental scenarios for both the 500 MW hydrogen production platform as for the compression platform (where hydrogen gas of 8 500 MW production platforms is gathered and injected into the pipeline to shore). Hydrogen is not continuously vented, only in case of emergencies when hydrogen needs to be released in a controlled manner. To determine the effect distances, two limits are regarded: (i) thermal radiation threshold for humans for an ignited release, (ii) lower flammability limit of hydrogen for an unignited release. The former gives lower distances, except that it also effects the area below the release, where an unignited only gives horizontal and upward vertical distances. From the resulting effect distances of the venting scenario, it is concluded that both the vertical as horizontal distances can be incorporated in the design of the vent pipe and platform. From the resulting effect distances of the accidental scenario's, it can be concluded that all horizontal distances are lower than the 500 m safety zone as defined by the Mining Act. The distances from the accidental scenario are significantly larger than the platform dimensions. These distances should not directly result in design alterations, since for these cases a complete risk assessment should be performed, which also includes the probability of failure which is very low for these cases.

Hydrogen is highly buoyant, which is in contrast to the behaviour of oxygen, which behaves as a neutral gas. This combined information leads to the recommendation to place the hydrogen vents at a higher position than the oxygen vents. This will prevent the mixing of the two flows.

Several assumptions have been made to get to these results, on which some discussion is possible.

- For all scenario's, it is assumed that the complete inventory can be released. This is a conservative assumption, since emergency shutdown valves or one-way valves will be located on each platform at several locations. These locations are not yet known, therefore this assumption is made. Including these locations will reduce the maximum volume to be released in an accidental situation, and therefore will reduce the effect distances.
- It is assumed that no increased oxygen concentration is present in the atmosphere. An increased oxygen concentration reduces the lower flammability limit, and therefore increase the effect distances of hydrogen gas releases. Therefore the oxygen vent should be located sufficiently far away from the hydrogen vent.

8 Conclusions and recommendations

Conclusions

- One of the goals of this research is to further investigate the attention points that came forward from the HAZID study. From this research no indications of any showstoppers for the development of an offshore hydrogen production platform are found.
- All systems in an hydrogen production platform which are changed compared to an offshore natural gas production platform are listed in this report. Two visuals are presented which include these systems and the links between them, one for a newly build platform, and one for a platform where the foundation structure of an existing platform is re-used.
- Consequence analyses for oxygen and hydrogen releases are performed. The distances and heights found for the scenarios and assumptions described in this report are given in Table 8.1. These distances can be used in the design process for determining the location and height of the vent stack in WP1. This is an iterative process, when the design changes, the consequence analyses should be revised.
- The maximum effect distance for an accidental hydrogen release does not exceed the 500 m no-entry zone as defined by the Mining Act.

Table 8.1 Summary of effect distances.

Scenario		Gas		Capacity	Max. vertical effect distance (concentration)	Max. horizontal effect distance (concentration)	Effect distance (heat flux)
Continuous	**Incidental**	**O_2**	**H_2**				
X		X		500 MW	30m	30m	-
X		X		4 GW	60m	180m	-
	X		X	500 MW	40m	10m	15m
	X		X	4 GW	70m	20m	20m

Recommendations

- Further research is recommended into the environmental consequences of releasing oxygen subsea or into the atmosphere and subsea discharge of brine solution from the desalinise system at large scale. Attention should be given to the materials used in the desalinise equipment and cleaning equipment at the water inlet to prevent marine growth.
- In case that multiple production platforms are located relatively close to each other, care should be taken that no interference between oxygen vent clouds and any of the platforms occurs. As long as two oxygen clouds do not interfere with each other the procedure from the current chapter can be used. If two oxygen clouds are expected to interfere a more detailed study like CFD (Computational Fluid Dynamics) is useful.
- More insight into possibilities to reduce the effect distances, such as pre-mixing with air, increasing the outflow velocity or increasing the outflow temperature.
- More insight into consequences of accidental scenarios for oxygen.
- Risk analysis for oxygen which also involves the probability of failure.
- In a later stage of the design, when locations of valves are known, the hydrogen release consequence analysis calculations should be repeated to determine more realistic distances.
- A study into the probabilities of failure of hydrogen pipes or piping should be performed. Because there is less experience with hydrogen transport, there is less heuristic data on probabilities of failure, but experience exists from natural gas transport.

- Guidelines or standards should include methodologies of risk assessments for hydrogen and oxygen release scenarios.
- For consequence analyses of both oxygen as hydrogen, one should carefully choose the software of use, since not all are validated for oxygen and especially not all for hydrogen. Different software could provide different results, but these should be negligible when validated software is used.

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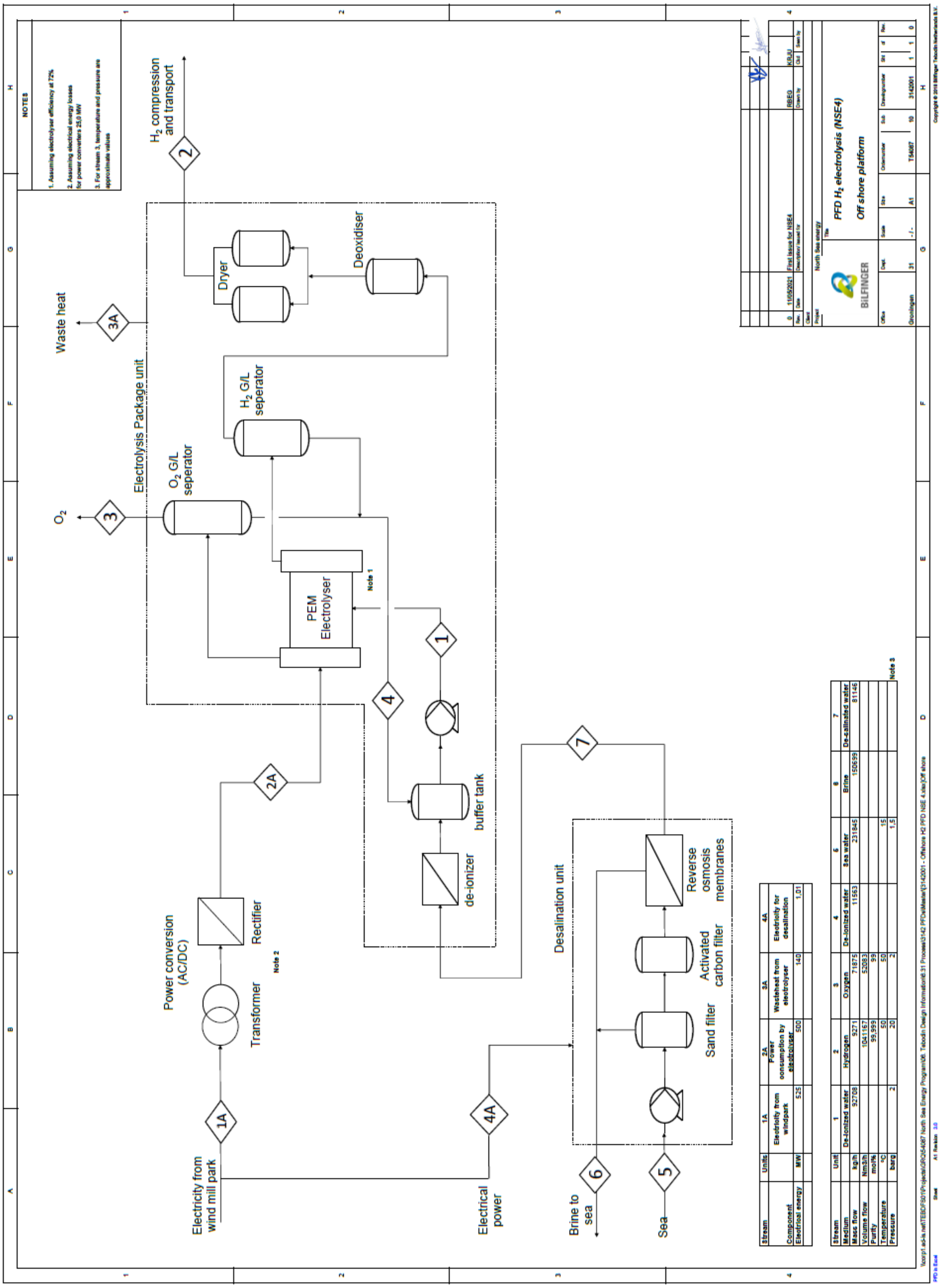
Appendix A
Hub West hydrogen generation platform



Stream	Units	1A	2A	3A	4A
Component		Electricity from windpark	Power consumption by electrolyser	Wasteheat from electrolyser	Electricity for desalination
Electrical energy	MW	525	500	140	1,01

Stream	Unit	1	2	3	4	6	6	7
Medium		De-ionized water	Hydrogen	Oxygen	De-ionized water	Sea water	Brine	De-salinated water
Mass flow	kg/h	92708	9271	71875	11563	231845	150699	81146
Volume flow	Nm3/h		1041167	52083				
Purity	mol%		99,999	99				
Temperature	°C		50	50		15		
Pressure	barg	2	20	2		1,5		

lay-out

Appendix B
List of safety and environmental critical parameters

This appendix gives a list of safety and environmental critical parameters (SECEs) subdivided into hardware barriers. The list given in this appendix is based mainly on Shell's Safety Critical Element Management Manual [18]. Figure 9.1 provides a visual of the hardware barriers as implemented by Shell.

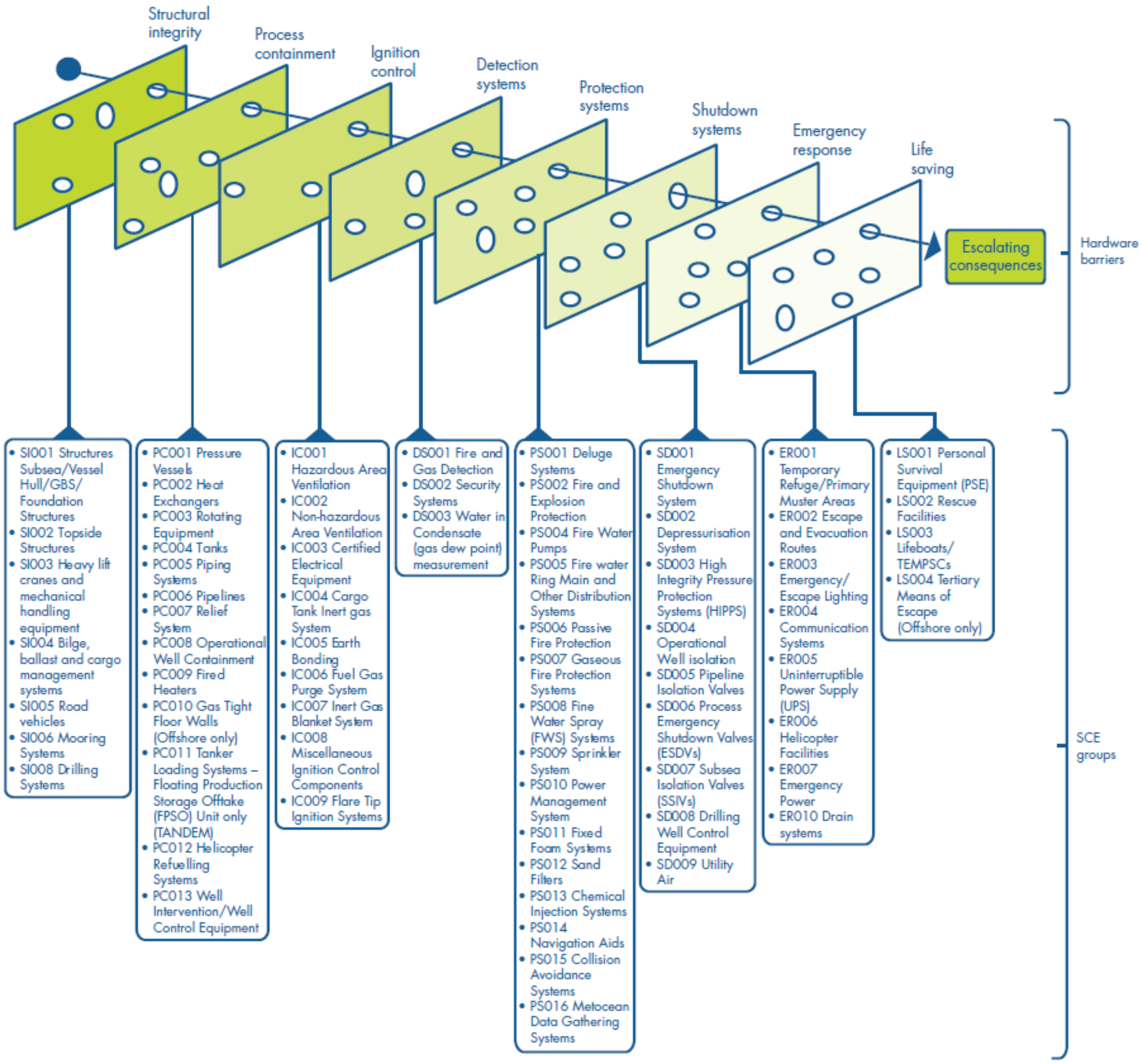


Figure 9.1: SECE barriers [18]

Structural integrity components

- Foundation structures or vessel hull
- Topside structure
- Heavy lift cranes and mechanical handling equipment
- Bilge, ballast and cargo management systems
- Road vehicles
- Mooring systems
- Drilling systems
- Helideck

Process containment systems

- Pressure vessels
- Heat exchangers
- Rotating equipment
- Tanks
- Piping systems
- Pipelines
- Operational well containment
- Fired heaters
- Gas tight floor walls (offshore only)
- Tanker loading systems – floating production storage offtake (FPSO) unit only (TANDEM)
- Helicopter refuelling systems
- Well intervention / Well control equipment

Ignition control systems

- Hazardous area ventilation
- Non-hazardous area ventilation
- Certified electrical equipment
- Cargo tank inert gas system
- Earth bonding
- Fuel gas purge system
- Inert gas blanket system
- Miscellaneous ignition control components
- Flare tip ignition systems

Detection control systems

- Fire and gas detection
- Security systems
- Water in condensate (gas dew point) measurement

Process containment relief systems

- Pressure relief system
- Relief system

Protection systems
- Deluge systems
- Fire and explosion protection
- Fire water pumps
- Fire water ring main and other distribution systems
- Passive fire protection
- Gaseous fire protection systems
- Fine water spray (FWS) systems
- Sprinkler system
- Power management system
- Fixed foam systems
- Sand filters
- Chemical injection systems
- Navigational aids
- Collision avoidance systems
- Metocean data gathering systems

Shutdown systems
- Emergency shutdown system
- Depressurisation system
- High integrity pressure protection systems (HIPPS)
- Operational well isolation
- Pipeline isolation valves
- Process emergency shutdown valves (ESDVs)
- Subsea isolation valves (SSIVs)
- Drilling well control equipment
- Utility air

Escape, evacuation and rescue equipment

Emergency response:
- Temporary refuge/primary muster areas
- Escape and evacuation routes
- Emergency/escape lighting
- Communication systems
- Uninterruptible power supply (UPS)
- Helicopter facilities
- Emergency power
- Drain systems

Life saving:
- Personal survival equipment
- Rescue facilities
- Lifeboats/TEMPSCs
- Tertiary means of escape (offshore only)

Appendix C
HAZID study NSE3

Below table presents a summary of the recommendations from the HAZID workshop review.

Action no.	Recommended Actions
[1]	Consider H2 detection and shutdown and depressurization
[2]	Perform a dispersion study on ventilation for H2
[3]	Consider minimising the H2 inventory
[4]	Investigate the blast peak of a explosion in respect to hydrocarbon explosions and impact on blast wall
[5]	Investigate if personal detection of H2 is required
[6]	Investigate if O2 measurement can detect O2 releases
[7]	Investigate the dispersion of O2
[8]	Consider to install PEM in a controlled environment with forced ventilation
[9]	Reduce O2 pressure as close to PEM electrolyser as possible
[10]	Investigate the impact on personnel health and safety requirements of high oxygen levels
[11]	Install fire detection suitable for H2 fires
[12]	Investigate the effect of the temperature of H2 fire on structural steel and TR and ESD (riser) valves and if the installed PFP is sufficient
[13]	Do not use deluge on H2 fires because H2 release will become unignited and form a cloud: possible explosion (see hazard 1a)
[14]	Investigate additional training of personnel for H2 fire detection and fire fighting
[15]	Investigate the implications of high voltage installation on the platform with respect to interaction on humans, explosions and EM interferences and footprint on the platform
[16]	Consider storage of inventory of any drainage as injecting in the export line is not feasible
[17]	Investigate best location to vent O2 and keep in mind vessels, helicopter, escape pods, life boats etc.
[18]	Investigate blowdown scenarios
[19]	Investigate best location to vent H2 and keep in mind vessels, helicopter, escape pods etc.
[20]	Check if CO2 extinguishing on vent is still feasible
[21]	Check if design of vent piping has sufficient strength to withstand an explosion of H2
[22]	Check purging of vent to ensure no fire in vent piping
[23]	Perform radiation study on H2 vent
[24]	Investigate brine sampling. Continuous measurement of O2 concentration in H2 recommended. Ensure calibration points are placed such that it will not be a potential ignition source
[25]	Investigate that the start-up and shutdown procedure considers purging of the installation. Further this subject needs to be more specified when design is more mature
[26]	Ensure that gas detectors are modified to detect H2
[27]	Investigate if there will be a cable to shore, which means auxiliary power is not required
[28]	Investigate if instrument air is required for typical operations
[29]	Investigate if hydraulic stems are required for typical operations
[30]	Investigate if cooling water can be used to reduce typical air cooling hazards
[31]	Ensure PEM is stopped on losing cooling medium

Action no.	Recommended Actions
[32]	Investigate how N2 is provided at the platform and ensure hazards associated with this installation are considered when design is more mature
[33]	No start-up without sufficient purging
[34]	Ensure sufficient buffer of N2 is available for safe shutdown of electrolyser
[35]	Ensure system (piping and equipment) is designed for these products
[36]	Investigate if pipeline is suitable (literature available)
[37]	Investigate the operating philosophy of the biocide/anti-scalant injection to the desalination unit and associated hazards
[38]	Install adequate firefighting equipment on electrical equipment
[39]	Do not use fire extinguishing systems in case of H2 fire (potential of explosions)
[40]	Relocate buffer vessel out of crane reach and/ or install sufficient protection
[41]	Provide sufficient lay-down areas outside any lifting areas from equipment at lower decks
[42]	Ensure PEM is located such that crane can reach the location taking into consideration favourable weather conditions and sea state
[43]	Vent study should also take into account corrosion on the installation
[44]	Ensure structure has sufficient strength for the intended lifetime
[45]	Ensure vessel is selected with sufficient dynamic positioning and minimize weight
[46]	All escape routes shall be reviewed since layout will change and also based on scenarios and radiation
[47]	Review if lifeboat can be lowered to sea, taking into consideration O2 vent
[48]	Ensure equipment can be maintained and reached by crane when required
[49]	Check area classification is suitable for H2

Appendix D
List of platforms in the North Sea

This appendix lists platforms on the Dutch continental shelf which have a topside weight larger or equal to a 500MW hydrogen production platform as designed in the NSE program. Table D.1 lists the platforms, cluster platforms that could hold the topside weight over multiple platforms are excluded, since a single platform for all production equipment is the focus of the NSE program. Note that the table lists some large weights, which do not always correspond to the appearance of the platform. It is therefore questionable whether the values in the OSPAR are unambiguously for a single platform or for a complex. Also note that not only gas platforms are listed.

Table D.1 Platforms on the Dutch continental shelf with a topside weight ≥9500 mT (OSPAR [23])

Name	Location	Operator	Installation	Weight sub-structure [mT]	Weight topside [mT]
F3-FB-1	F-Block	Neptune Energy Netherlands B.V.	2009	50000 (concrete)	9500
L13-FE-1	L-Block	Nederlandse Aardolie Maatschappij BV	1989	7117	9550
AME-2	AME	Nederlandse Aardolie Maatschappij BV	1983	9411	9840
K8-FA-2	K-Block	Nederlandse Aardolie Maatschappij BV	1977	19400	23654
K15-FA-1	K-Block	Nederlandse Aardolie Maatschappij BV	1976	18200	43367
L2-FA-1	L-Block	Nederlandse Aardolie Maatschappij BV	1990	10755	44292
K14-FA-1	K-Block	Nederlandse Aardolie Maatschappij BV	1976	18200	45197
K8-FA-3	K-Block	Nederlandse Aardolie Maatschappij BV	1984	19400	45600
K14-FA	K-Block	Nederlandse Aardolie Maatschappij BV	1985	16072	50402
K15-FB-1	K-Block	Nederlandse Aardolie Maatschappij BV	1978	10245	50681
K8-FA-1	K-Block	Nederlandse Aardolie Maatschappij BV	1976	19243	53614
L13-FC-1	L-Block	Nederlandse Aardolie Maatschappij BV	1985	17604	56535
Ameland-Westgat-1	Ameland-Westgat	Nederlandse Aardolie Maatschappij BV	1984	8800	75000
L9-FF-1	L-Block	Nederlandse Aardolie Maatschappij BV	1996	22209	106800

North Sea Energy offshore system integration

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