**Master's thesis**

**NTNU**
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Sean Kristian Condon

# Environmental aspects of offshore $H_2$ production from offshore wind farms

Master's thesis in Energy and Environmental Engineering
Supervisor: Francesco Cherubini
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# Abstract

Transitioning from fossil fuels to low-carbon alternatives, including hydrogen, is crucial to reduce greenhouse gas (GHG) emissions while meeting the global energy demand. An expected global increase in hydrogen demand has given Norway the potential to contribute as a large-scale producer of green hydrogen. Through an extensive literature review and life cycle assessment (LCA), this project explores the possibilities and environmental impacts of offshore hydrogen production through the utilization of co-located offshore electrolyzers at offshore wind farms along the Norwegian coast. The analysis identified a baseline scenario incorporating floating offshore wind turbines, proton-exchange membrane (PEM) electrolysis, pipeline transportation, onshore compression and storage, and domestic truck distribution. Findings from the conducted LCA estimated an environmental impact for all evaluated scenarios, mainly in the range of 1 - 2 kg $CO_2$-eq./kg $H_2$, when excluding the impact from hydrogen leakage, primarily due to emissions from steel production for the offshore turbines. The baseline scenario specifically yielded an impact of 1.32 kg $CO_2$-eq./kg $H_2$. Notably, shifting to bottom-fixed turbines and salt cavern storage demonstrated the most significant positive environmental impact, giving a best-case scenario, which integrated these environmentally favorable alternatives, an impact of 0.95 kg $CO_2$-eq./kg $H_2$. In contrast to previous literature, this research included the environmental impact from hydrogen leakage. The assessment revealed that a hydrogen leakage rate of 5% and a GWP100 impact of eight resulted in an environmental impact of 0.42 kg $CO_2$-eq./kg $H_2$, which yielded a total environmental impact of 1.74 kg $CO_2$-eq./kg $H_2$ for the baseline scenario. Moreover, when considering shorter-lived gases using the GWP20 metric, the impacts of hydrogen leakage were even higher. Despite Norway's promising potential, achieving a maximum reduction of climate impact during a large-scale transition to a hydrogen economy necessitates both the reduction of hydrogen leakage rates and the increased production of green hydrogen through more sustainable material production pathways.

# Norwegian summary

Overgangen fra fossile brensler til lavkarbonalternativer, inkludert hydrogen, er avgjørende for å redusere utslippet av klimagasser samtidig som den globale energietterspørselen imøtekommes. En forventet økning i global hydrogenproduksjon og etterspørsel har gitt Norge potenisalet til å bidra som en storstilt produsent av grønt hydrogen. Gjennom en omfattende litteraturgjennomgang og livssyklusanalyse (LCA) utforsker dette prosjektet mulighetene og miljøkonsekvensene ved produksjon av hydrogen til havs ved bruk av elektrisitet fra havvind langs den norske kysten. Analysen identifiserte et grunnleggende scenario som omfattet flytende havvind, proton-utveksling membran (PEM) elektrolyse, rørledningstransport, komprimering og lagring på land, og innenlandsk distribusjon med lastebiler. Resultatene fra livsløpsanalysen estimerte en miljøpåvirkning for alle evaluerte scenarioer hovedsakelig i området 1 - 2 kg $CO_2$-ekv./kg $H_2$, når man ekskludererte påvirkningen fra hydrogenlekkasje, primært på grunn av utslipp fra stålproduksjonen til vindturbinene. Grunnscenarioet resulterte i en innvirkning på 1.32 kg $CO_2$-ekv./kg $H_2$. Det viste seg at overgangen til bunnfast havvindteknologi og lagring i saltgruver hadde den mest positive miljøpåvirkningen i hydrogenverdikjeden. Som et resultat oppnådde det beste scenariet, som integrerte disse miljømessig gunstige alternativene, et utslipp på 0.95 kg $CO_2$-ekv./kg $H_2$. I motsetning til tidligere litteratur inkluderte denne forskningen miljøpåvirkningen fra hydrogenlekkasje. Vurderingen avdekket at en hydrogenlekkasjerate på 5% og en GWP100-påvirkning på åtte, resulterte i en miljøpåvirkning på 0.42 kg $CO_2$-ekv./kg $H_2$. Dette ga deretter en total miljøpåvirkning på 1.74 kg $CO_2$-ekv./kg $H_2$ for grunnscenarioet. Videre, når man vurderte kortlevde gasser ved hjelp av GWP20 vurdering, var påvirkningen fra hydrogenlekkasje enda høyere. Til tross for Norges lovende potensial, kreves det både reduksjon av hydrogenlekkasjer og økt produksjon av grønt hydrogen gjennom mer bærekraftige metoder for å oppnå maksimal reduksjon av klimapåvirkingen under en storstilt overgang til en hydrogenøkonomi.

# Preface

This thesis concludes my Master of Science in Energy and Environmental Engineering, carried out at the Department of Energy and Process Engineering at the Norwegian University of Science and Technology spring 2023. It is a continuation of the project work carried out in the fall of 2022.

I would like to express gratitude towards my supervisor Prof. Francesco Cherubini for great guidance the last year. Also, a special thanks to my co-supervisor Marcos Djun Barbosa Watanabe, for his contributions, valuable feedback, and meaningful discussions during this period.

I would also like to thank all my fellow classmates for making these five years both social and fun as well as educational.

Norwegian University of Science and Technology
Trondheim, June 2023

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# Nomenclature

| **Units** | |
|---|---|
| GW | gigawatt |
| kg $CO_2$-eq./kg $H_2$ | kilogram carbon dioxide equivalents per kilogram hydrogen |
| kWh/kg $H_2$ | kilowatt hour per kilogram hydrogen |
| Mt | Million tonne |
| MW | megawatt |
| tkm | tonne kilometer |
| t/km | tonne per kilometer |
| **Abbreviations** | |
| BOP | Balance of Plant |
| CCS | Carbon Capture and Storage |
| EFTA | European Free Trade Association |
| GHG | Greenhouse Gas |
| GLO | Geographical Location Global |
| GUI | Graphical User Interface |
| GWP | Global Warming Potential |
| HVDC | High-Voltage Direct Current |
| IAI | International Aluminium Institute |
| IEA | International Energy Agency |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| LNG | Liquefied Natural Gas |
| LOHC | Liquid Organic Hydrogen Carrier |
| PEM | Proton-Exchange Membrane |
| RER | Europe |
| RoW | Rest of World |

# 1 Introduction

## 1.1 Background and motivation

Anthropogenic emissions due to the constantly increasing demand for energy have accelerated one of humanity's most significant challenges, climate change. A rapid increase in global temperature has resulted in a myriad of adverse effects on both human and planetary health, from disruption in food systems and loss of agricultural productivity to severe increases in extreme weather events and worsening human health conditions [1]. The primary contributors to these phenomenons are greenhouse gases (GHG), which include carbon dioxide ($CO_2$), methane ($CH_4$), nitrous dioxide ($N_2O$), and fluorinated gases emitted from the combustion of fossil fuels [2]. In the coming decades, replacing fossil fuels with low-carbon alternatives, such as fuels with significantly lower carbon intensity or renewable energy, is crucial to meet the future demand for energy together with the global climate commitments targeting to limit global warming below 2 degrees Celsius, preferably 1.5 degrees Celsius [3].

Global $CO_2$ emissions from energy combustion and industrial processes reached a record high level in 2022 with a total emission of 36.8 gigatonnes [4]. This is a level closer to 20 times the amount of emissions emitted in 1900, showing the need for immediate action to reduce GHG emissions. Hydrogen and hydrogen-based fuels, with their vast potential in terms of application, are expected to play a pivotal role in this issue. Hydrogen is applicable in numerous segments of the energy sector and is anticipated to grow sixfold from today's levels to meet 10% of total final energy consumption by 2050 [5]. Globally, there are significant ambitions linked to an increased usage of hydrogen in the energy mix and as an input factor to industrial processes. However, hydrogen production is currently largely confined to fossil fuels, mainly from natural gas without carbon capture and storage (CCS), also known as grey hydrogen. This is due to a range of technical and economic factors, with gas prices and capital expenditures being the two most important [6]. The global annual emissions from the hydrogen industry, therefore, amount to around 900 Mt $CO_2$, comparable to the total global emissions from air traffic or shipping [5]. Such a practice cannot continue in a world targeting net zero emissions by 2050. Low-carbon hydrogen produced from renewable energy (green) or fossil fuels with CCS (blue) must therefore become more competitive within the next decades as hydrogen demand is expected to rise due to replacing fossil fuels in a variety of applications [5].

Green hydrogen has emerged as an energy carrier with the potential to mitigate local, national, and global emissions while creating economic value for businesses [7]. By storing renewable electricity during times of peak or excess power generation to be utilized during times of demand, it presents the benefit of flexibility to the power grid by increasing reliability and resilience [6].

As a result, there has been an expected increase in the number of countries implementing policies directly supporting investment in hydrogen technologies, spanning the numerous sectors they target. The anticipated rise of hydrogen production in future climate-friendly scenarios [5] and the significance of hydrogen in the energy transition present several opportunities for Norway as both an energy and a technology nation. Norway has a vast opportunity to become a large-scale exporter of clean hydrogen produced from renewable energy sources, providing a rapid ramp-up of production and end use in multiple sectors will take place [7].

Norway annually produces around 225 000 tonnes of hydrogen, primarily as a feedstock in chemical industries and refineries of petroleum-based products [8]. There are many indications that green hydrogen will become an important part of Norway's future energy system, as the industrial, transportation, and energy sectors all have the potential to generate increased demand for hydrogen produced through electrolysis. Furthermore, the conditions for hydrogen development are ideal as Norway has several years of industrial experience across the hydrogen value chain from the gas, petroleum, and maritime industries, together with an abundance of renewable energy sources [7]. The Norwegian Government has therefore implemented a hydrogen strategy to emphasize the importance of clean hydrogen to reach the ambitious national and international emission targets by 2050. This strategy defines clean hydrogen as hydrogen derived from renewable energy or natural gas with CCS technology. As offshore wind is one of the largest growing renewable energy sources worldwide, it has a vast potential to be combined with hydrogen [9]. Over the past years, the growth of large-scale offshore wind farms has become clearly noticeable in Europe due to reduced costs and improved performance from technological advances in wind turbines and foundation structures, giving offshore wind a strong foothold in Europe with close to 18.5 GW installed capacity in 2019 [10]. With this growth, offshore wind has a global potential to reach more than 100 GW by 2030, continuing exponentially towards 2050.

This has led to a potential approach involving the production of hydrogen from offshore electrolyzers co-located at offshore wind farms to facilitate distribution to Norway and exportation to Europe. A system converting electricity to hydrogen offshore will address the disadvantages of a typical set-up with high-voltage direct current (HVDC) cables, such as transmission losses, power faults, high installation costs, and difficulties connected to step-up and step-down of the voltage [11]. There are several ongoing pilot and pre-commercial projects in Europe exploring this interesting approach and the related technologies, with PosHYdon [12] in the Netherlands, Deep Purple [13] in Norway, Lhyfe [14] in France, and Dolphyn [15] in the UK, to mention some of them. Nevertheless, there are still significant environmental and techno-economic uncertainties regarding this option, which this project explores.

## 1.2 Literature review

There is a mutual understanding that power from offshore wind fluctuates greatly, rendering it suitable for conversion into hydrogen for various purposes, including storage and transportation. As this section presents, the main focus of the literature concentrates on the environmental impact of a system defined from the production of hydrogen through electrolysis to distribution.

In general, findings conclude that the production stage is responsible for the main environmental impact in all cases regarding the transportation of gaseous hydrogen through pipelines, with an impact in the range of 1 - 2 kg $CO_2$-eq./kg $H_2$ throughout the system's lifetime. The study by *Wulf et al. (2018)* [16] evaluated three different hydrogen production pathways, including cavern versus tank storage and pipeline versus trailer transportation, all produced from onshore alkaline water electrolysis powered by wind power. By varying the mass flow through the pipelines and transportation distance, a total of seven cases were evaluated. The research conducted by *Schaefer (2022)* [17], on the other hand, assessed an offshore hydrogen production system with a main focus on storage technology, investigating compressed hydrogen stored in underground formations and liquid organic hydrogen carriers (LOHC) stored on a floating vessel. In both mentioned studies, results presented considerably higher global warming potential (GWP) values due to larger impacts from the storage and transportation stages.

This was also the case for the analysis performed by *Noh, Kang, and Seo (2023)* [18], which considered value chains utilizing liquefied hydrogen, LOHC, ammonia ($NH_3$), as well as compressed hydrogen. The system evaluated these cases based on offshore wind power and offshore wind + grid to operate the electrolysis and included all stages until onshore storage. By comparing the results in the study, LOHC showed the highest GWP values due to electricity usage for conditioning and storage, followed by $NH_3$, liquefied hydrogen, and compressed hydrogen. The study by *Weidner, Tulus, and Guillén-Gosálbez (2023)* [19] included an additional comparison of green hydrogen produced from solar PV technology. However, this study did not include transportation and storage in the assessment as the main focus laid around the comparison of production from different electricity sources.

The literature review led to a general conclusion that transportation of compressed hydrogen through pipelines was a favorable option due to a lower environmental impact. A summary of results from different cases from the reviewed literature is shown in Table 1.1. It is also worth mentioning that most studies introduced the concept of hydrogen losses and impacts such as embrittlement. However, they rarely included the environmental impact of hydrogen leakage to the atmosphere through losses in the value chain.

**Table 1.1:** Overview of results from reviewed LCA studies. Note that none of the studies have included the hydrogen leakage impact.

| **Hydrogen value chain** | **Assumptions** | **[kg $CO_2$-eq./kg $H_2$]** |
|---|---|---|
| Compressed $H_2$ production + salt cavern storage + pipeline transport (10, 40, 80 tons per day) + dispersion (fueling station) | Wind electricity | 1.71, 1.52, 1.53 [16] |
| Offshore compressed $H_2$ production + compression + underground $H_2$ storage + pipeline transport | Offshore wind electricity | 1.43 - 2.64 [17] |
| Offshore compressed $H_2$ production + conditioning + ship transport + postprocessing + storage | Offshore wind electricity | 1.15 [18] |
| Onshore green $H_2$ production | Wind electricity | 1.05 [19] |
| Compressed $H_2$ production + LOHC-tank + trailer transport (100 km and 400 km) + dispersion (fueling station) | Wind electricity | 4.96, 5.84 [16] |
| Offshore compressed $H_2$ production + hydrogenation + LOHC storage + dehydrogenation | Offshore wind electricity | 1.84 - 4.96 [17] |
| Offshore electrolysis + LOHC-conditioning + ship transport + postprocessing + storage | Offshore wind electricity | 2.05 - 10.11 [18] |
| Onshore green $H_2$ production | Solar PV electricity | 3.8 [19] |

### 1.2.1 Hydrogen leakage

Studies implied several challenges linked to the large-scale implementation of hydrogen in the existing energy system. While zero-emission and low-carbon hydrogen hold great potential to help solve pressing energy challenges, hydrogen is a short-lived indirect greenhouse gas with a high leakage potential due to its small molecule composition [20]. When hydrogen is emitted into the atmosphere, around 70% to 80% is estimated to be removed by soils via diffusion and bacteria, while the remaining 20% to 30% is oxidized by reacting with naturally occurring hydroxyl radical (OH). Hydrogen oxidation contributes to climate change by increasing concentrations of other GHGs. It results in less OH available to react with methane, which leads to a longer atmospheric lifetime for methane. Production of atomic hydrogen leads to a series of reactions, eventually forming ozone. Oxidation also increases the amount of water vapor, which, together with methane and ozone, all result in global warming. Hydrogen leakage rates are, therefore, a concern when evaluating hydrogen-related projects.

The commonly used 100-year global warming potential (GWP100) metric fails to accurately reflect the warming potential of short-lived gases like hydrogen over shorter timescales [20]. However, research has been conducted investigating the GWP100, displaying hydrogen's significant impact on the environment. Results showed GWP100 values of 5.8 [21], 8 ± 2 [22], 11 ± 5 [23], and 12.8 ± 5.2 [24]. A previous study [20] also showed that worst-case hydrogen leakage rates could yield a near-doubling in radiative forcing relative to fossil fuel counterparts in the first five years following the technology switch. At the same time, it yields an 80 % decrease in radiative forcing over the following 100 years after deployment. Figure 1.1 shows the total relative climate impact of replacing fossil fuel systems with hydrogen for the first 100 years. In short, hydrogen leakage will have a much larger environmental impact in the first years compared to after 100 years, resulting in a potential increase in warming when switching from fossil-based technology to hydrogen.

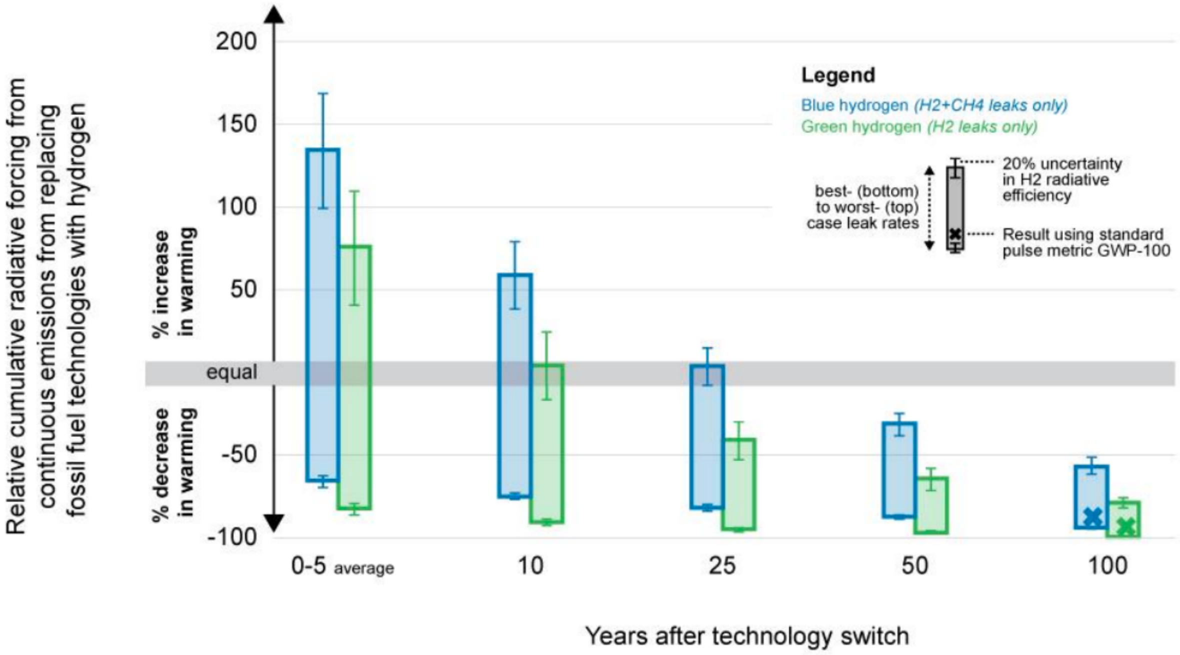

**Figure 1.1:** Relative climate impact over time from the replacement of fossil fuel systems with green or blue hydrogen. The figure presents the best- to worst-case leak rates over a time period of 100 years, showing the potential increase or decrease in warming. **Figure source**: Ocko, I. and Hamburg, S. (2022) [20]

Hydrogen's small molecule size, low molecular weight, high diffusivity, and low viscosity make it challenging to contain, and it can, therefore, easily leak from the infrastructure through the value chain [20]. Detecting hydrogen leakage also poses several challenges, as currently, no commercially available sensors can detect leakage levels well below the threshold for hydrogen gas flammability. Accordingly, it is very likely that may hydrogen leak throughout the value chain. However, which components contribute the least and most to leakage is unclear due to given lack of data. Leakage in the value chain will depend on the configuration of the pathway from production to end use, but previous studies estimate a leakage range from 0.3% to 20% [20]. All reviewed studies acknowledge the major uncertainty in the estimates due to the lack of data.

## 1.3 Research objective

This project has the primary purpose of exploring the potential and possibilities for offshore hydrogen production from offshore wind farms off the Norwegian coast. There are several studies providing a life cycle assessment (LCA) on similar offshore hydrogen production cases. However, this work aims to present a broader scope presenting new value chains and including the environmental impact of hydrogen losses. The main objectives of this study will review the questions listed below:

- What environmental impacts are associated with offshore hydrogen production from offshore wind farms along the Norwegian coast?
- Which components in the offshore hydrogen production value chain have the largest impact, and what are potential improvements to reduce emissions?
- How large is the environmental impact from hydrogen leakage through losses in the defined system?

Through a review of relevant literature on offshore hydrogen production, this project will investigate the key technologies involved in offshore wind electricity generation, electrolysis, hydrogen transportation, storage, and distribution. Possible scenarios for the offshore hydrogen value chain will be identified, and life-cycle inventories (LCI) for a baseline scenario and three alternative scenarios based on techno-economic aspects and challenges will be developed. An LCA will then be conducted to assess the environmental aspects of offshore hydrogen production. The impact and main barriers of each major stage in the life cycle will be evaluated, and future opportunities and technical improvements will be discussed.

# 2 Methods

In environmental and sustainability research, methodology plays a crucial role in determining the reliability and validity of the findings. In this chapter, the methods employed in defining the different scenarios are explored, and a life cycle inventory for the life cycle assessment has been compiled. The identified scenarios and compiled inventories are based on previously reviewed literature and are a continuation of the project work carried out in the fall of 2022.

## 2.1 Identification of baseline scenario

A fundamental understanding of the offshore hydrogen value chain and the different technologies included was gained through the literature review combined with general research on the topic. With this knowledge, a baseline scenario was identified, consisting of floating offshore wind turbines for electricity production, proton-exchange membrane (PEM) electrolysis to convert electricity to hydrogen, pipeline transportation from sea to onshore, compression of hydrogen to 350 bar for compressed hydrogen in storage tanks, and domestic truck distribution.

Floating offshore wind turbines were chosen as the favorable technology due to an estimate that over 80% of all the offshore wind energy resources lie in waters deeper than 60 meters where traditional bottom-fixed installations are not feasible [25]. Floating offshore wind not only allows improved access to more wind resources, but it also relies less on seabed conditions, which was thought to result in a minor environmental impact in terms of interference with marine ecosystems at the seabed [26].

The hydrogen production was situated on an offshore platform. This implied that area requirements would be a significant driver due to crucial space occupation on the platform when evaluating electrolyzer technology. A compact system design was, therefore, a decisive factor. Due to a combination of prominent advantages such as rapid system response, the high outlet pressure of 30 to 40 bar [27], compact system design, and overall high efficiency, the PEM electrolysis was selected for the baseline scenario. The efficiencies of this technology ranged from 80% to 90% [28]. The hydrogen production stage also included reverse osmosis, when water is demineralized or deionized through a semi-permeable membrane [29]. Both the electrolyzer and reverse osmosis process were powered by electricity from the offshore wind farm. Accordingly, the electricity consumption was subtracted from the overall wind farm electricity output available for hydrogen production.

A hydrogen pipeline was chosen as the favorable method for the baseline scenario for transportation. This was due to pipeline transportation being identified as the most cost-efficient option for distances below 1 500 - 3 000 km [5] and offering a continuous mass flow compared to the other transportation options. The hydrogen was compressed as this is the most widely used storage method [30], and there is estimated an undesirable large energy demand related to liquefaction and the Haber-Bosch process for ammonia production, which are two alternative options. The compressed hydrogen was then stored in high-pressure storage tanks at 350 bar onshore before being distributed domestically by truck.

As seen in Figure 2.1, the baseline scenario was built up by six major stages. Three of the stages in the value chain were exchanged to evaluate the potential of different scenarios, shown in the next subsection.

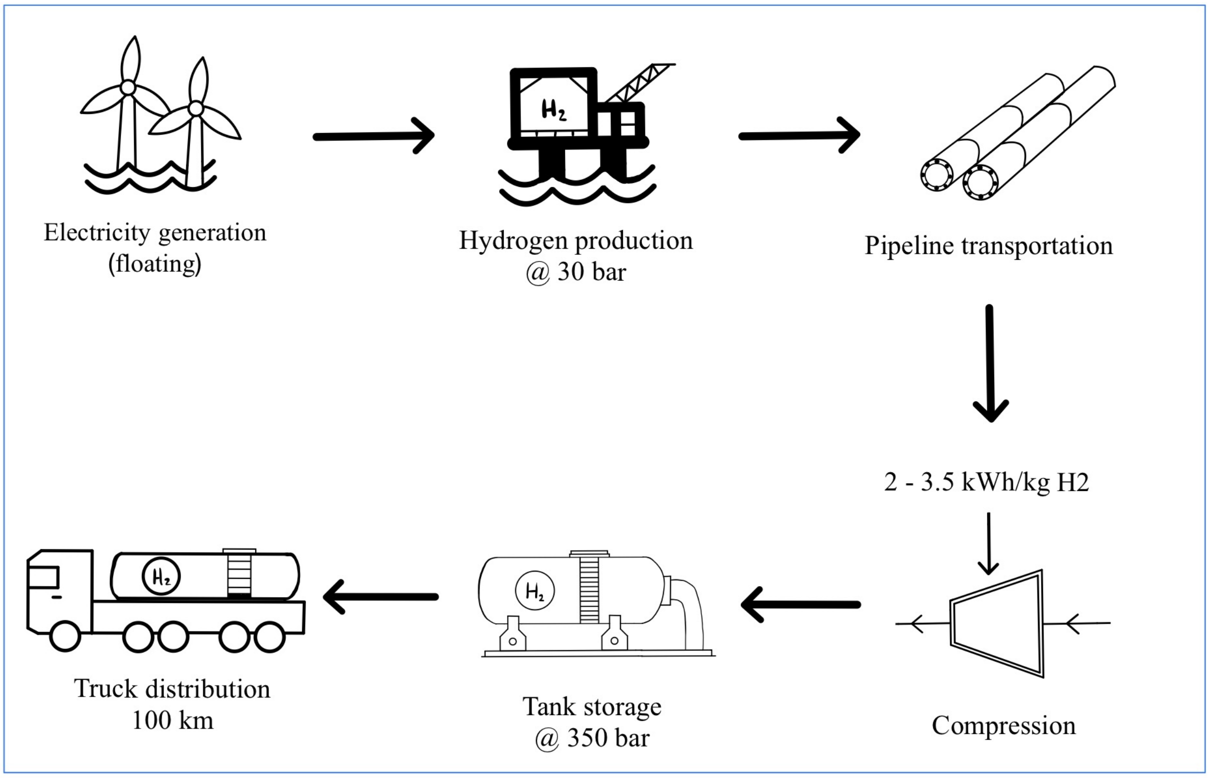

**Figure 2.1:** Illustration of production stages in baseline scenario

### 2.1.1 Alternative scenarios

#### Bottom-fixed offshore wind turbines

The first alternative scenario explored a bottom-fixed offshore wind farm instead of floating while maintaining the same value chain after this stage. An illustration of the main steps is provided in Figure 2.2.

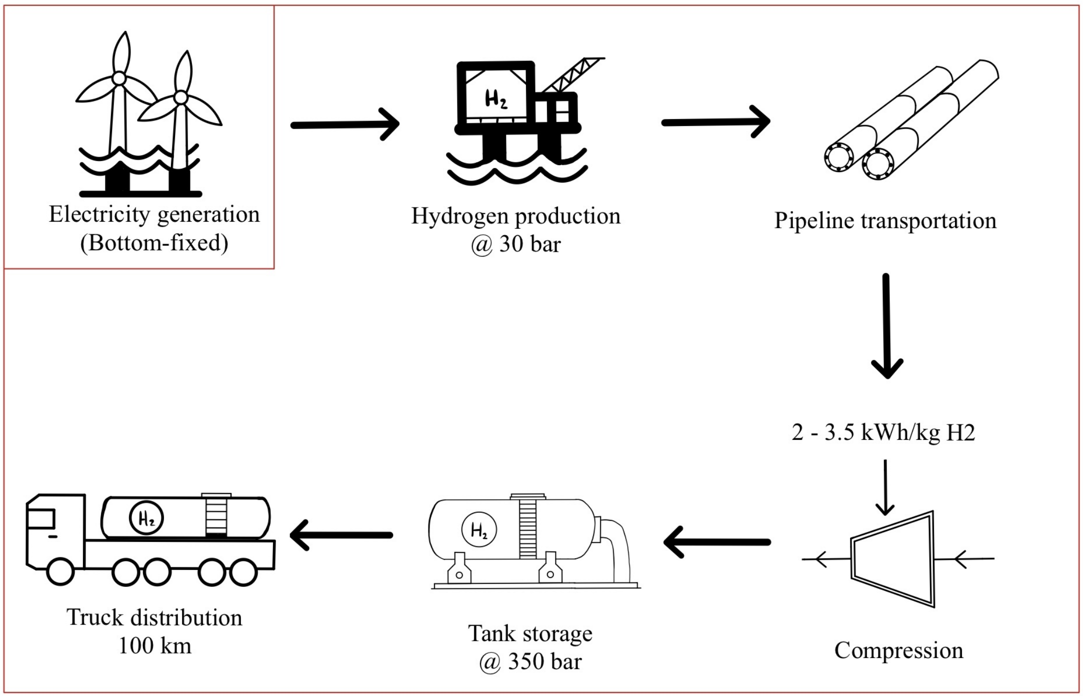

**Figure 2.2:** Illustration of production stages in alternative scenario 1 (bottom-fixed)

### Shipping distribution

The second alternative scenario explored distribution by shipping. All other steps in the value chain remained the same as for the baseline scenario. An illustration of the main steps is provided in Figure 2.3.

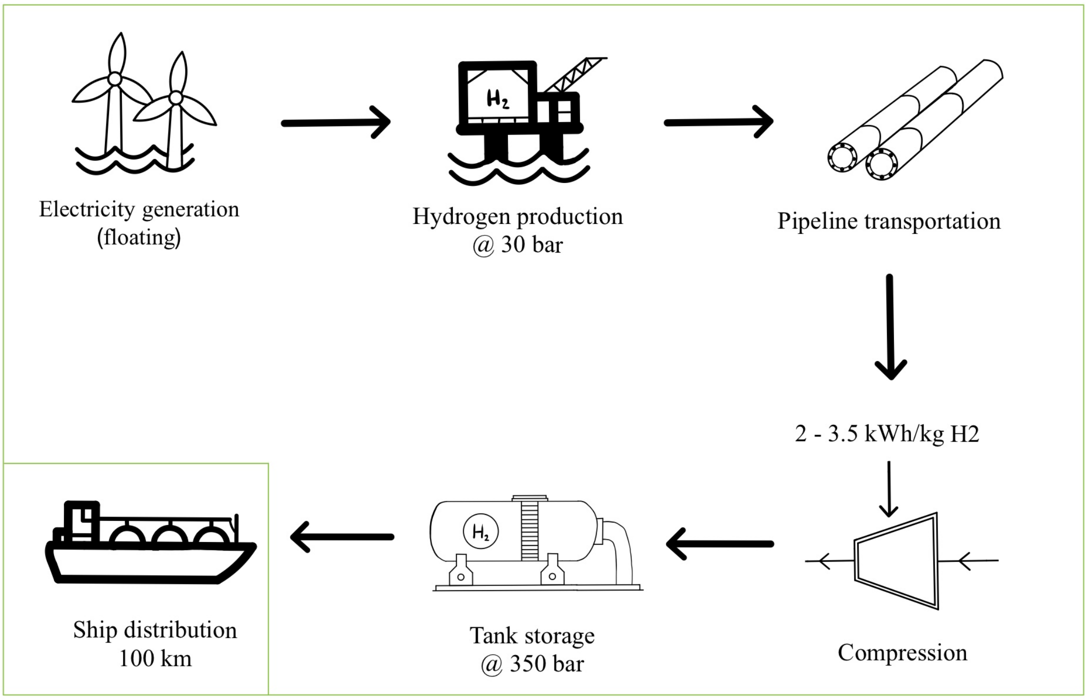

**Figure 2.3:** Illustration of production stages in alternative scenario 2 (shipping)

### Salt cavern storage

The third scenario explored salt cavern storage. Salt cavern storage is an underground hydrogen storage method created by solution mining. Salt slowly dissolves and produces brine by pumping water into the salt formation [31]. The resulting brine is then extracted and leaves room for a large, tight cavern where hydrogen can be stored under pressure. All other steps in the value chain remained the same as for the baseline scenario. An illustration of the main steps is provided in Figure 2.4.

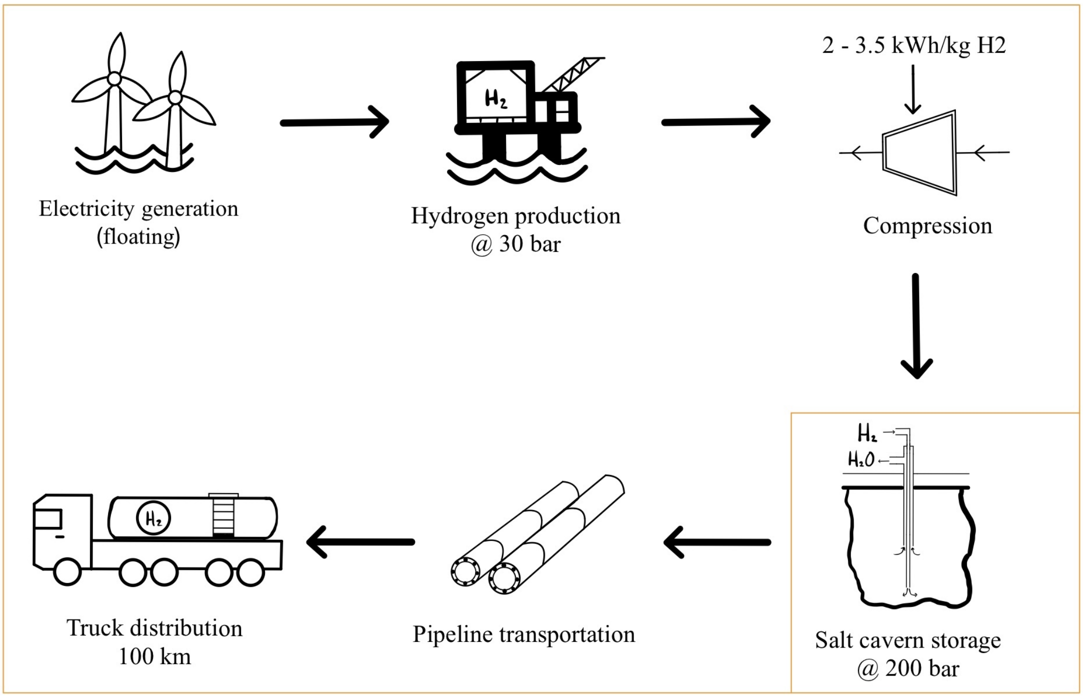

**Figure 2.4:** Illustration of production stages in alternative scenario 3 (salt cavern)

## 2.1.2 Project location

The Norwegian Ministry of Petroleum and Energy has started a consultation process on the proposed division of areas to be allocated in the two areas, Utsira Nord and Sørlige Nordsjø II (shown in Figure 2.5). These were both potential areas for an offshore hydrogen production project. Sørlige Nordsjø II has a maximum potential of 3000 MW, utilizing both bottom-fixed and floating structures for the wind turbines. Utsira Nord, on the other hand, has a maximum potential of 1500 MW and is mainly focused on floating technology [32]. As the scenarios evaluated both floating and bottom-fixed turbines, the Sørlige Nordjø II field was a reasonable choice of location for the offshore hydrogen production system. This was also a sensible choice due to the possibilities for hydrogen storage in salt caverns located within reach, as seen in Figure 2.6. This was under the assumption that the salt structures in this area would be usable.

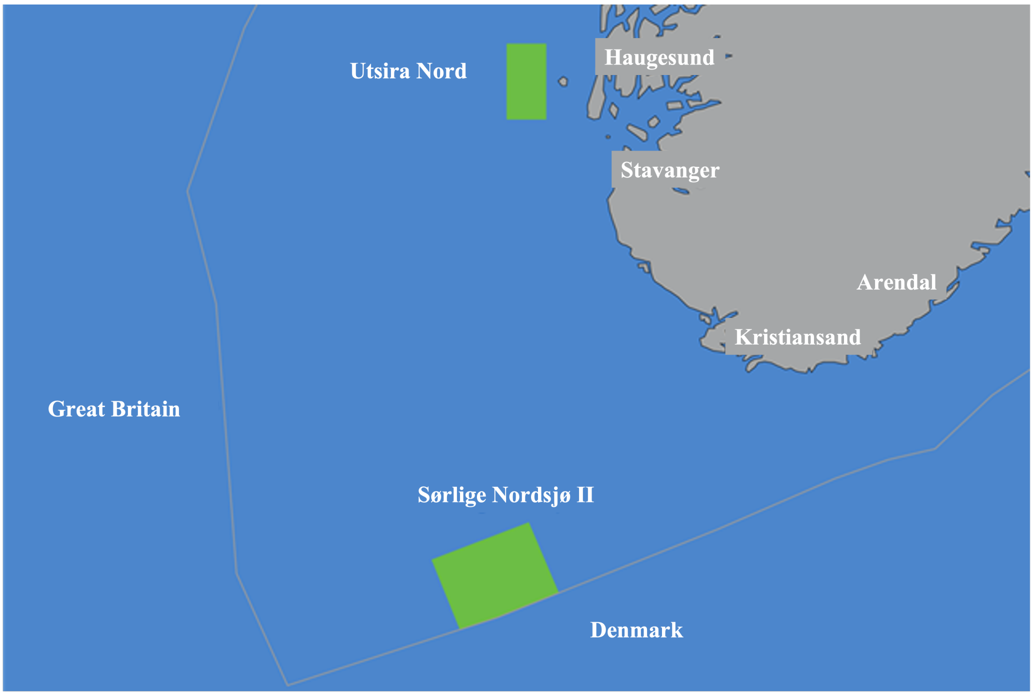

**Figure 2.5:** Location of the Norwegian offshore wind fields Utsira Nord and Sørlige Nordsjø II. **Figure source:** NVE (distributed by Viseth (2022) [33])

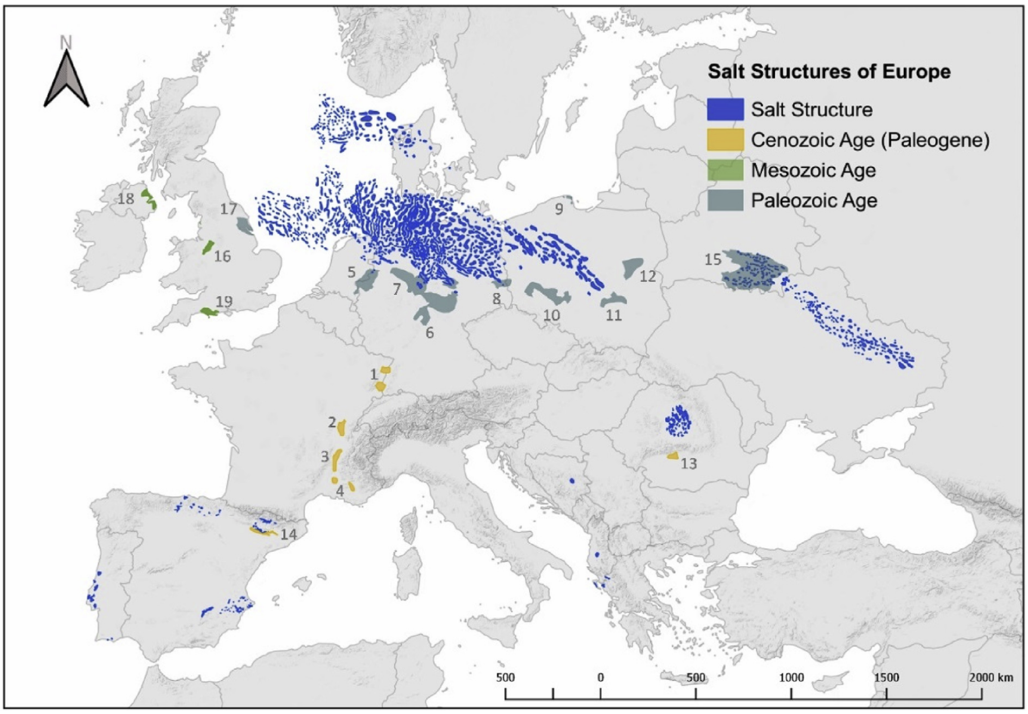

**Figure 2.6:** Location of salt structures in Europe and the Northern Sea. Note that these salt structures are only potential locations for salt cavern storage. Salt structures are assumed to be usable for the sake of the project location. **Figure source:** Caglayan et al. (2020) [34]

This potential for hydrogen salt caverns was derived through a previous study on salt cavern storage [34], where the total cavern storage potential for Norway was concluded to be around 6 000 TWh located offshore. Sørlige Nordsjø II lies around 200 km off the Norwegian coast and mainland, resulting in the set distance for further calculations being set to 200 km.

### 2.1.3 Project size calculations

Today's new offshore wind power projects have a turbine capacity in the range of 8 to 12 MW [35]. However, a 5 MW capacity wind turbine was chosen for this case due to available data on material, available LCA reports, and experience with the given capacity.

To dimension the system and estimate the size of the offshore wind farm, an assumption of hydrogen mass flow of 0.3 kg $H_2$/s or 1080 kg $H_2$/h through the pipeline was set. This value was based on previous work [36], together with the assumptions of a pipeline inlet pressure of 30 bar and outlet pressure of 24 bar. The size of the electrolyzer was then calculated from the mass flow by multiplying it by the demand for electricity to produce hydrogen. The energy content of 1 kg hydrogen is around 120 MJ (LHV), equal to 33.3 kWh [37]. Together with an assumption of an electrolyzer efficiency of 80%, this resulted in a demand of 41.63 kWh/kg $H_2$. By multiplying the mass flow (1080 kg $H_2$/h) and demand (41.63 kWh/kg $H_2$), a 45 MW sized electrolyzer was attained. The lifetime for 1 MW electrolyzers was estimated to be around ten years [38], resulting in the need for 90 electrolyzers to cover the entire twenty years lifetime of the system.

An assumed power demand of 3 kWh/kg $H_2$ [39] to the compressor for hydrogen compression to 350 bar and 0.045 kWh/kgH2 for reverse osmosis for water used in the electrolysis process resulted in the actual power output from the offshore wind farm being estimated to be 56.5 MW. Energy requirements throughout the system can be seen in Table 2.1.

**Table 2.1:** Energy requirements, utilized from the produced electricity from the wind farm

| Activity | Energy requirement |
|---|---|
| Power consumption electrolyzer | 49.25 kWh/kg $H_2$ [40] |
| Reverse osmosis | 0.04545 kWh/$H_2$ water [17] |
| Compressor | 3 kWh/kg $H_2$ [39] |

As new offshore wind projects have capacity factors of 40% to 50% [41], an average value of 45% was assumed for the capacity factor. As shown in calculations in Table 2.2, the size of the baseline scenario offshore wind farm was estimated to be around 110 MW, which corresponded to 22 floating offshore wind turbines. The expected lifetime for such a system was 20 years, which resulted in 175 200 operating hours. As the wind turbines occasionally are being maintained, a factor of 0.98 [42] was multiplied to gain total operating hours equal to 171 696. This resulted in around 185 500 000 kg of hydrogen being produced throughout the project's lifetime. However, with an assumed hydrogen loss rate of 5% [20] throughout the value chain due to hydrogen leakage, with 2.5% of the hydrogen loss occurring in the pipeline and 2.5% loss in the storage stage, it resulted in around 176 225 000 kg of usable hydrogen during the system's lifetime. Hydrogen's GWP100 was set to eight based on estimations from the literature review mentioned in Section 1.2.1 and was predicted to have a shifting impact depending on the percentage of hydrogen leakage. Thus, the yearly hydrogen production from this system corresponded to around 4% of Norway's current annual hydrogen production [8].

**Table 2.2:** Calculations of the total size of the offshore wind farm, based on estimated mass flow. For simplicity, the size of the wind farm was assumed 110 MW.

| **Mass flow [kg $H_2$/s]** | **[kg $H_2$/h]** | **Power electrolyzer [MW]** | **Wind power [MW]** | **Wind farm [MW]** |
|---|---|---|---|---|
| 0.3 | 1080 | 45 | 48.2 | 107.2 |

A summary of the main assumptions and baseline scenario reference values is listed in Table 2.3.

**Table 2.3:** Reference values for the baseline scenario

| **Reference data** | |
|---|---|
| Distance to shore | 200 km |
| Capacity wind farm | 110 MW |
| Wind farm capacity factor | 45% |
| Capacity electrolyzer | 45 MW |
| Electrolyzer efficiency | 80% |
| Mass flow | 0.3 kg $H_2$/s |
| Number of turbines | 22 |
| Number of electrolyzer stacks | 90 |
| Lifetime system | 20 years |
| Hydrogen leakage | 5% |
| Hydrogen produced throughout lifetime | 185 500 000 kg |
| Hydrogen delivered throughout lifetime | 176 225 000 kg |

## 2.2 Life cycle assessment, LCA

LCA is a methodology for assessing environmental impacts associated with all the stages in a life cycle, in this case, for the different stages in offshore hydrogen production. This project involves a thorough inventory of the energy and materials required across the value chain and calculates the corresponding environmental emissions. The primary reason for utilizing LCA for such research was due to the widely recognized and standardized procedures [43].

### 2.2.1 Goal and scope definition

This project aims to investigate and explore the potential for offshore hydrogen production by utilizing electricity from offshore wind farms. It also has the means of establishing preferred and alternative production routes for offshore hydrogen production and detecting which of the analyzed options yields the lowest environmental impact. This goal will contribute to determining the feasibility and potential for offshore hydrogen production off the Norwegian coast.

The project will primarily be centered around the LCA and environmental aspects of the system. Therefore, the main focus will be on the impact category of global warming potential over 100 years (GWP100). The functional unit in this project will be kg $H_2$ produced and delivered over the project's lifetime.

A selection of assumptions, together with the goal, sets a foundation for defining the scope of the system. The scope includes electricity production from offshore wind turbines and ends with the distribution of hydrogen. The scope excludes minor parts of the system which are believed to have a lesser environmental impact, such as electrical cables from the turbines to the hydrogen platform, emissions directly from the drilling and well process in the salt cavern scenario, and material used for the reverse osmosis process. Emissions related to maintenance and decommissioning throughout the system are also excluded. A general approach for assessing and evaluating the project's defined components is included without a deeper technical assessment. Therefore, the main life cycle stages included in the analysis are narrowed to the production and processing of all infrastructure material related to the system and the fuel consumption related to the transportation offshore to install the system. The impact of hydrogen losses emitted in the atmosphere is also included.

Incomplete or missing data in the inventories have been replaced with existing values in Ecoinvent 3.8 database. At some stages in the value chain, data for hydrogen-specific components have been replaced with data for natural gas components or other available data. This is the case for the hydrogen platform, where a natural gas platform was assumed to be a sufficient substitute for our hydrogen platform. It is also the case for distribution, where natural gas ships have been determined as a sufficient replacement. As the specific inventory for hydrogen compressors is not found, air-compressor data is assumed.

### 2.2.2 Life cycle inventory, LCI

In this section, detailed life cycle inventories have been compiled for each stage in the baseline and alternative scenarios. As GHG emissions were assumed to be most significant for material usage and fuel consumption during installation, this was the focus of the inventory. Stages such as maintenance and decommissioning were placed outside this project's scope, as mentioned in the previous subsection.

A mass inventory for floating offshore wind with materials and weight distribution of the different components has been obtained and summarized in Table 2.4 and Table 2.5. The values presented in the tables were based on three different sources for 5 MW floating offshore wind turbines from previous project work. These sources relied on various foundations, resulting in a range of values when assessing the weight distribution of the wind turbine. The results, therefore, showed the minimum, average, and maximum values for each component in one turbine. However, only the average values were used for further calculations.

**Table 2.4:** Weight of different components in one floating offshore wind turbine, based on the three sources: [44], [45], [46]

| **Components** | **Weight [tons]** | | |
|---|---|---|---|
| | *Minimum* | *Average* | *Maximum* |
| Nacelle | 239 | 239.7 | 240 |
| Rotor | 110 | 110 | 110 |
| Tower | 241 | 379.3 | 647 |
| Foundation | 939 | 2454.5 | 3550 |
| Total | 1529 | 3183.5 | 4547 |

Based on the calculated average value, the mass distribution of the materials in one 5 MW offshore wind turbine is shown in Table 2.5. This table includes the activity name, unit, amount, and production location based on data from a set of sources and Ecoinvent 3.8 database.

**Table 2.5:** Inventory for one 5 MW floating offshore wind turbine based on Ecoinvent 3.8 and the three sources: [44], [45], [46]

| Amount | Unit | Activity | Location |
|---|---|---|---|
| 19 000 | kilogram | market for cast iron | GLO |
| 4 500 | kilogram | market for copper, cathode | GLO |
| 2 481 000 | kilogram | market for steel, low-alloyed | GLO |
| 11 300 | kilogram | market for aluminium, primary, ingot | IAI Area, EU27 & EFTA |
| 228.06 | cubic meter | market for concrete, normal | RoW |
| 1 300 | kilogram | market for electronics, for control units | GLO |
| 1 300 | kilogram | market for polyethylene terephthalate, granulate, bottle grade | GLO |
| 53 000 | kilogram | market for glass fibre reinforced plastic, polyamide, injection moulded | GLO |

The first alternative scenario evaluated bottom-fixed offshore wind turbines. Therefore, a mass inventory for this case has been compiled with the same approach as for floating offshore wind. Table 2.6 and Table 2.7 show the mass distribution and materials used in one turbine. Two of the three sources used were based on 5 MW bottom-fixed offshore wind turbines, while the last source was scaled from a 2 MW turbine to match 5 MW.

**Table 2.6:** Weight of different components in one bottom-fixed offshore wind turbine, based on the three sources: [47], [48], [49]

| Components | Weight [tons] | | |
|---|---|---|---|
| | *Minimum* | *Average* | *Maximum* |
| Nacelle | 154.5 | 218.9 | 251.3 |
| Rotor | 82 | 115.3 | 134 |
| Tower | 259 | 296.8 | 346.3 |
| Foundation | 801 | 4994.3 | 8744.3 |
| Total | 1296.5 | 5625.3 | 9475.9 |

**Table 2.7:** Inventory for one 5 MW bottom-fixed offshore wind turbine based on Ecoinvent 3.8 and the three sources: [47], [48], [49]

| Amount | Unit | Activity | Location |
|---|---|---|---|
| 119 200 | kilogram | market for cast iron | GLO |
| 6 100 | kilogram | market for copper, cathode | GLO |
| 859 300 | kilogram | market for steel, low-alloyed | GLO |
| 77 600 | kilogram | market for steel, chromium steel 18/8 | GLO |
| 4 700 | kilogram | market for aluminium, primary, ingot | IAI Area, EU27 & EFTA |
| 1164 | cubic meter | market for concrete, normal | RoW |
| 700 | kilogram | market for zinc | GLO |
| 1 717 000 | kilogram | market for gravel, crushed | RoW |
| 52 600 | kilogram | market for epoxy resin, liquid | RER |
| 18 300 | kilogram | market for glass fibre reinforced plastic, polyamide, injection moulded | GLO |

PEM electrolyzers were determined as the preferred electrolyzer technology due to their compact design resulting in less area required, a high output pressure of 30 bar, and a fast response time as mentioned in Section 2.1. The electrolyzer required a lot of specific materials, such as platinum, Nafion, and iridium, as well as several other metals and materials. As Nafion and iridium were not available in the Econivnet database, polyethylene terephthalate and platinum were used as proxies. A list of materials for the electrolyzer system has been accumulated in Table 2.8. This includes materials for a 1 MW PEM stack based on the current values from previous work [38].

**Table 2.8:** LCI for electrolyzer per MW stack [38].

| Amount | Unit | Activity | Location |
|---|---|---|---|
| 4.5 | kilogram | market for copper, cathode | GLO |
| 0.825 | kilogram | market for platinum | GLO |
| 528 | kilogram | market for titanium | GLO |
| 27 | kilogram | market for aluminium, primary, ingot | IAI Area, EU27 & EFTA |
| 100 | kilogram | market for steel, chromium steel 18/8 | GLO |
| 16 | kilogram | market for polyethylene terephthalate, granualte, bottle grade | GLO |
| 9 | kilogram | market for activated carbon, granular | GLO |

Estimates for the balance of plant (BOP), referring to all the supporting components and auxiliary systems needed for the hydrogen electrolysis stack, are given in Table 2.9.

**Table 2.9:** LCI for PEM BOP per MW stack [38]

| Amount | Unit | Activity | Location |
|---|---|---|---|
| 100 | kilogram | market for copper, cathode | GLO |
| 5.6 | cubic meter | market for concrete, normal | RoW |
| 4 800 | kilogram | market for steel, low-alloyed | GLO |
| 1 900 | kilogram | market for steel, chromium, steel 18/8 | GLO |
| 100 | kilogram | market for aluminium, primary, ingot | IAI Area, EU27 & EFTA |
| 300 | kilogram | market for polyethylene terephthalate, granualte, bottle grade | GLO |
| 1 100 | kilogram | market for electronics, for control units | GLO |
| 200 | kilogram | market for lubricating oil | RER |

The lifetime of the electrolyzer system was assumed to be 10 years for the PEM stack and 20 years for the BOP. It was also assumed a constant capacity throughout the lifetime, which yielded a constant hydrogen production rate throughout the system's lifetime.

The production of hydrogen occurred on an offshore platform. The PEM stack's surface area had to be estimated to fit on the platform deck. Based on interpolated data from 100, 200, 400, and 800 MW electrolyzer systems, the area estimation for the system was around 3500 m$^2$ [50]. As available data on hydrogen-specific platforms was limited, a natural gas platform was assumed and accepted as a proxy. The data for this natural gas offshore platform was available in Ecoinvent 3.8 database as shown in Figure 2.10.

**Table 2.10:** Market activity for offshore platform per unit [51]

| Amount | Unit | Activity | Location |
|---|---|---|---|
| 1 | unit | market offshore platform, natural gas | GLO |

Pipeline transportation of compressed hydrogen was the main technology for both the baseline scenario and the alternative scenarios. An assumption of a pipeline diameter in the range of 100 to 150 mm [36], a wall thickness of 25 mm [17], and a total pipeline length of 200 km enabled an estimate of the total pipeline material volume, which was equal to around 1080 m$^3$. By assuming a 100% steel pipeline with a density equal to 7850 kg/m$^3$, the total mass of the pipeline was calculated to be around 8477 tons, which was equal to 42.4 t/km. Hydrogen transmission pipeline values from Premise [52], summarized in Table 2.11, were estimated to be around 43.8 t/km. As this was a good match to the defined case study, it would be an acceptable option to continue with to have a consistent inventory.

**Table 2.11:** LCI for transmission pipeline per km pipeline [52]

| **Amount** | **Unit** | **Activity** | **Location** |
|---|---|---|---|
| 21 800 | kilogram | drawing of pipe, steel | RER |
| 225 000 | kilogram | market for silica sand | GLO |
| 9 000 | cubic meter | excavation, skid-steer loader | RER |
| 4 390 | tonne-kilometer | market for transport, freight, lorry, unspecified | RER |
| 21 800 | kilogram | market for steel, low-alloyed | GLO |
| 1 200 | cubic meter | excavation, hydraulic digger | RER |
| 13 600 | tonne-kilometer | market for transport, freight train | Europe w/o Switzerland |
| 64.8 | kilogram | market for aluminium alloy, AlLi | GLO |
| 86.1 | kilogram | market for zinc | GLO |
| 19 | kilogram | market for silicone product | RER |
| 0.0024 | kilowatt hour | market group for electricity, low voltage | GLO |
| -10 900 | kilogram | treatment of decommissioned pipeline, natural gas, inert material landfill | CH |

The energy required for hydrogen compression to 350 bars was estimated to be between 2 and 3.5 kWh/kg $H_2$ [53]. The material composition of a compressor was mainly made up of low-alloyed steel (78%), high-alloyed steel (14%), iron (5%), and other metals (3%) [54]. However, as the specific inventory for hydrogen compressors was not found, air-compressor data was therefore adapted, as shown in Table 2.12. By linearly scaling from previous work [17], around 17 compressors were estimated for the specific case. As the impacts from electricity consumption would prevail in this stage, the compressor infrastructure and material composition impacts were expected to be negligible.

**Table 2.12:** LCI for air-compressor per unit [51]

| **Amount** | **Unit** | **Activity** | **Location** |
|---|---|---|---|
| 1 | unit | air compressor, screw-type compressor, 300kW | RER |

For the storage facility, the main technology was compressed hydrogen tanks, with one alternative scenario based on salt cavern storage. The life cycle inventory for a high-pressure storage tank per kg of hydrogen was obtained from Premise [52]. A 5% hydrogen loss throughout the system was assumed, and for simplicity, 50% of the loss was to take place before storage, in the pipelines, and the remaining in the storage and distribution stage. This loss was a result of hydrogen leakage based on the literature review in Section 1.2.1. The hydrogen leakage rate was thought to vary largely due to large uncertainty and limited data available, and how a varied leakage rate would impact the results was therefore looked closer upon. For the baseline scenario, the loss was set to 5% based on an assumption with background from estimates from previous work [20]. This meant that the daily storage capacity equaled 24 780 kg of hydrogen. The compiled inventory is shown in Table 2.13, with an assumed lifetime of 20 years. The inventory for the salt cavern was mainly made up of materials for a well system and riser to transport hydrogen up and down from the platform to the salt cavern. Table 2.14 shows the inventory for this scenario. Note that the functional unit for the salt cavern case is for total produced hydrogen throughout the system lifetime instead of per kg hydrogen produced.

**Table 2.13:** LCI for high-pressure storage tank per kg hydrogen [52]

| Amount | Unit | Activity | Location |
|---|---|---|---|
| 3.06 | kilogram | market for epoxy resin, liquid | RER |
| 0.9 | kilogram | market for sheet rolling, chromium steel | GLO |
| 0.9 | kilogram | market for sheet rolling, steel | GLO |
| 0.9 | kilogram | market for steel, chromium steel 18/8 | GLO |
| 0.9 | kilogram | market for steel, low-alloyed | GLO |
| 0.6 | kilogram | market for sheet rolling, aluminium | GLO |
| 0.6 | kilogram | market for aluminium alloy, AlLi | GLO |
| 0.45 | kilowatt hour | market group for electricity, low voltage | GLO |
| 7.14 | kilogram | market for carbon fibre reinforced plastic, injection moulded | GLO |

**Table 2.14:** LCI for high-pressure well system and riser to the salt cavern for total produced hydrogen throughout the system lifetime [17]

| Amount | Unit | Activity | Location |
|---|---|---|---|
| 104 373 | kilogram | market for steel, low-alloyed | GLO |
| 104 130 | kilogram | market for steel, chromium steel 18/8 | GLO |
| 208 413 | kilogram | market for hot rolling, steel | GLO |
| 208 413 | kilogram | market for drawing of pipe, steel | GLO |
| 0.744 | kilogram | market for zinc | GLO |
| 87 781 | kilogram | market for cement, Portland | Europe w/o Switzerland |

Transporting hydrogen domestically by truck was chosen as the distribution method for the baseline scenario. As fuel consumption was expected to prevail in this stage, material demand and assembly of the truck would be excluded. To calculate the fuel consumption in tkm (tonne-kilometer), data from Ecoinvent 3.8 was used. The data for truck transportation used is shown in Table 2.15. This activity represents a generic market combining data for transport which was calculated for an average load factor, including empty return trips. The vehicle operates with diesel and represents delivering the service of transportation of 1 tonne across a distance of 1 kilometer. For the defined case, transportation distance was estimated at 100 km, resulting in 17 600 000 tkm.

**Table 2.15:** Market activity for truck distribution per tonne-kilometer [51]

| Amount | Unit | Activity | Location |
|---|---|---|---|
| 1 | tonne-kilometer | market for transport, freight, lorry, unspecified | RER |

This was then compared to the alternative scenario of distributing hydrogen by shipping. Hydrogen shipping vessels are described as an emerging technology, and the world's first hydrogen tanker completed its first maritime transport of liquefied hydrogen in early 2022 [55]. Due to technological immaturity and the lack of data on hydrogen shipping, an estimated proxy of transport in deep-sea liquefied natural gas (LNG) tankers from Ecoinvent 3.8 was assumed. Table 2.16 shows an overview of the activity.

**Table 2.16:** Market activity for ship distribution per tonne-kilometer [51]

| Amount | Unit | Activity | Location |
|---|---|---|---|
| 1 | tonne-kilometer | market for transport, freight, sea tanker for liquefied natural gas | GLO |

This activity was also based on a generic market delivering the service of transportation of liquid goods by a tanker for LNG. As LNG has a volumetric density of 426 kg/m$^3$ [56], and compressed hydrogen at 350 bars has 26.1 kg/m$^3$ [57], a conversion of the values was needed to be able to use this activity as a proxy. Assuming no changes in the vessel volumetric cargo capacity, a factor of 16 was multiplied to estimate the tonne-kilometer, which resulted in 281 600 000 tkm for the distance of 100 km.

Offshore installation of components was an essential factor when assessing an offshore hydrogen system. As fuel consumption would be the main driver of impacts and emissions in the installation phase, fuel type and consumption had to be determined. The impact of emissions to the air from burning diesel and heavy fuel oil was based on values from *IMO (2020)* [58]. Vessels used to install foundations and wind turbines, and corresponding work time and fuel consumption can be found in Table 2.17. Values in the table were based on values from previous work on offshore wind production [49]. Due to the unequal number of wind turbines from the obtained values, the estimated values were scaled linearly to match the baseline scenario. Irrelevant processes containing values for bottom-fixed installation are highlighted in orange and have been excluded for the cases of floating offshore wind turbines.

**Table 2.17:** Transportation vessels required for installation of offshore farm [49]

| Activity | Fuel type | Work time [days] | Fuel consumption [l/h] |
|---|---|---|---|
| Excavator | Diesel | 75 | 0.455 |
| Barge for excavator | Heavy fuel oil | 75 | 100 |
| Barge for disposal of seabed material | Heavy fuel oil | 56.3 | 100 |
| Vessel for transport of rock for stone bed | Heavy fuel oil | 113.9 | 100 |
| Vessel for dumping of rock for stone bed | Heavy fuel oil | 75 | 100 |
| Tugboats for transport foundation | Diesel | 50 | 322.6 |
| Jack-up for foundation | Heavy fuel oil | 25 | 170 |
| Tugboats for jack-up vessel | Diesel | 50 | 322,6 |
| Vessel for transport of rock for scour protection | Heavy fuel oil | 113.9 | 100 |
| Vessel for dumping of rock for scour protection | Heavy fuel oil | 75 | 100 |
| Jack-up transport and installation turbines | Heavy fuel oil | 25 | 170 |
| Tugboats for jack-up vessel | Diesel | 50 | 322,6 |

A summarized version of the baseline scenario is presented in Table 2.18. This includes all the units and kilograms of the different components inserted in the LCA throughout the system's lifetime.

**Table 2.18:** Baseline scenario components in LCA

| Amount | Unit | Activity |
|---|---|---|
| 22 | unit | Floating offshore wind turbine |
| 1 | unit | Platform |
| 90 | unit | Electrolyzer |
| 200 | kilometer | Pipeline |
| 17 | unit | Compressor |
| 24 780 | kilogram | Storage tanks |
| 1.762E+07 | tonne-kilometer | Truck distribution |
| 1 | unit | Offshore installation |

### 2.2.3 Data verification and validation

The results were severely dependent on the background data derived in the previous sections. It was crucial that the data utilized was trustworthy to create realistic and acceptable results. The data for the offshore wind turbines was based on a multitude of diverse sources, and a 5 MW capacity wind turbine was selected as a base value. This decision was made due to the greater availability of experience and data for this specific case. Furthermore, the technology maturity of the chosen system created a limitation due to missing applicable data on hydrogen-specific components. To compensate, proxy data was assumed and was therefore considered as a possibility for error. The installation phase also presented some uncertainties since the obtained data relied on a single source and was subsequently linearly scaled to ensure comparability with this project's defined system. Due to the limited number of existing commercial projects, the available data for a complete system was limited. This was solved by exploring and collecting data for each stage in the supply chain separately. However, combining these individual datasets into a more extensive system introduced a level of uncertainty.

### 2.2.4 Life cycle impact assessment, LCIA

In this thesis, the tools Brightway and Ecoinvent were used to conduct the LCA. The open-source software Activity Browser provided a graphical user interface (GUI) for the Brightway LCA framework. To supply sufficient background data for the LCA, the database Ecoinvent was used. The Ecoinvent database is a life cycle inventory database providing various sustainability assessments. It enables users to gain a deeper understanding of the environmental impacts of specific products and services. This database contains more than 18 000 activities modeling human activities and containing information on industrial or agricultural processes, such as measuring the natural resource withdrawn from the environment, the emissions released into the water, soil, and air, the products required from other processes, and the co-products and waste produced [59]. The version Ecoinvent 3.8 was chosen for this project, and for some cases, a modified Ecoinvent database was used based on Premise software.

Many impact categories could be looked closer at when evaluating the environmental impact of a project. For the specific case, the impact category of climate change assessing the global warming potential would be the most important impact, and large segments of the results and discussion were therefore fixated on this. However, to gain a broader understanding of the environmental impact, other impact categories were also assessed. Moreover, ReCiPe Midpoint (H) was chosen as the method for impact assessment with a primary focus on GWP100.

# 3 Results and discussion

This section includes the derived results from the LCA, presenting findings from the main impact category (climate change, GWP) together with a discussion of the results. To gain a deeper understanding of the results, a sensitivity analysis further investigated some of the more important aspects determined from the results.

## 3.1 Global warming potential (GWP)

Based on the compiled inventories, an LCA was conducted to determine the environmental impact from both the baseline and alternative scenarios. Figure 3.1 presents some key findings from the LCA impact category climate change GWP100, showing the impact from each component in the supply chain divided by the total delivered hydrogen for each scenario. The figure currently disregards the impact of hydrogen leakage. Upon closer inspection of the different scenarios evaluated, it becomes apparent that the most impactful modification involves shifting to bottom-fixed offshore wind, followed by salt cavern storage, which outperforms storage tanks, and minimal impact from changes in the distribution method, as trucks and shipping, have a similar impact. This resulting data was then utilized to develop a best-case scenario that integrated the favorable environmental alternatives.

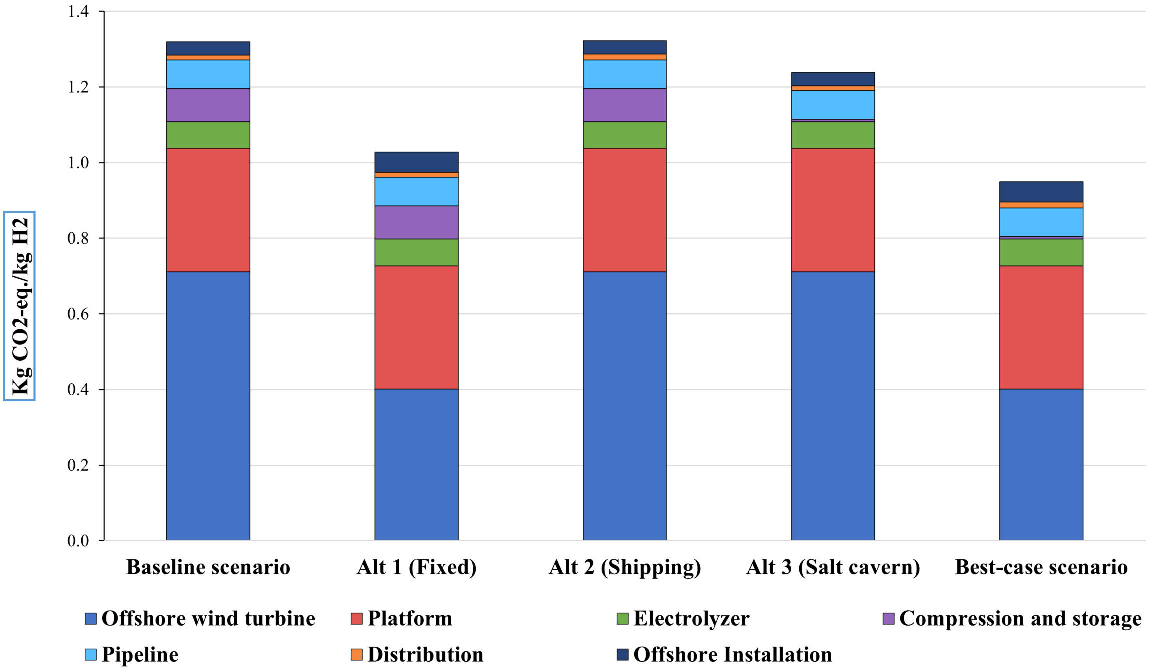

**Figure 3.1:** Emissions excluding the impact from hydrogen leakage from the components in various scenarios. Results indicate favorable modifications for bottom-fixed turbines and salt cavern storage.

The analysis of the components in all scenarios revealed that offshore wind turbines were accountable for the majority of emissions. This observation was derived from Figure 3.1

showing the distribution throughout the supply chain, where a considerable impact from the offshore platform with electrolyzers also was detected. A summary of the GWP100 impacts for components in the baseline scenario is shown in Table 3.1. As the focus of the assessment was situated around material consumption, this was an understandable result due to the components for the electricity generation and hydrogen production representing a more significant proportion of the total weight. Though several of the studies reviewed in Section 1.2 excluded the specific technology used in the production phase from their scope, most studies assumed and included the impact of electricity generation from wind power. The findings, therefore, corresponded well with these studies as they likewise estimated the preeminent impact of the production phase due to the extraction and raw materials processing for the construction of the wind turbines.

**Table 3.1:** Results of component distribution, climate change GWP100 [kg $CO_2$-eq./kg $H_2$]

| **Offshore wind turbine** | **Platform** | **Electrolyzer** | **Compression** |
|---|---|---|---|
| 0.712 | 0.326 | 0.071 | 0.001 |
| **Storage** | **Pipeline** | **Distribution** | **Offshore installation** |
| 0.086 | 0.075 | 0.013 | 0.035 |

Results showed that the baseline scenario had an estimated climate footprint of around 1.32 kg $CO_2$-eq./kg $H_2$, primarily due to carbon dioxide when excluding the impact from hydrogen leakage. The best-case scenario, on the other hand, only emitted around 0.95 kg $CO_2$-eq./kg $H_2$. Nevertheless, hydrogen leakage through losses in the value chain had a significant environmental impact on the defined system. Both impacts, with and without hydrogen leakage impact, can be found in Table 3.2.

**Table 3.2:** LCA results, climate change GWP100, with and without hydrogen leakage impact, functional unit [kg $CO_2$-eq./kg $H_2$]

| **Scenarios** | **Baseline** | **Alt 1** | **Alt 2** | **Alt 3** | **Best-case** |
|---|---|---|---|---|---|
| Excluding $H_2$ loss | 1.320 | 1.028 | 1.322 | 1.238 | 0.946 |
| Including $H_2$ loss | 1.741 | 1.449 | 1.743 | 1.659 | 1.367 |

As seen from the results, the estimated impact from the offshore hydrogen production system mainly laid between 1 and 2 kg $CO_2$-eq./kg $H_2$. Despite a variation in the supply chain, this was a similar result to the other LCA reports discussed in the previous Section 1.2. In contrast to the previous work, the impact of hydrogen leakage was included. This was responsible for a considerable impact of around 0.42 kg $CO_2$-eq./kg $H_2$ for all evaluated cases as shown in Figure 3.2. As mentioned in Section 1.2.1, hydrogen leakage has a significant environmental impact. A GWP100 value of eight [22] was assumed for all cases, together with a total of 5% hydrogen loss throughout the system's lifetime. Although there was a high range of uncertainty in the literature, 5% was assumed as a reasonable average value based on the literature review in Section 1.2. The significant impact of hydrogen leakage is evident, and in the forthcoming sensitivity analysis 3.3, the outcomes obtained by varying the percentage of hydrogen loss are presented.

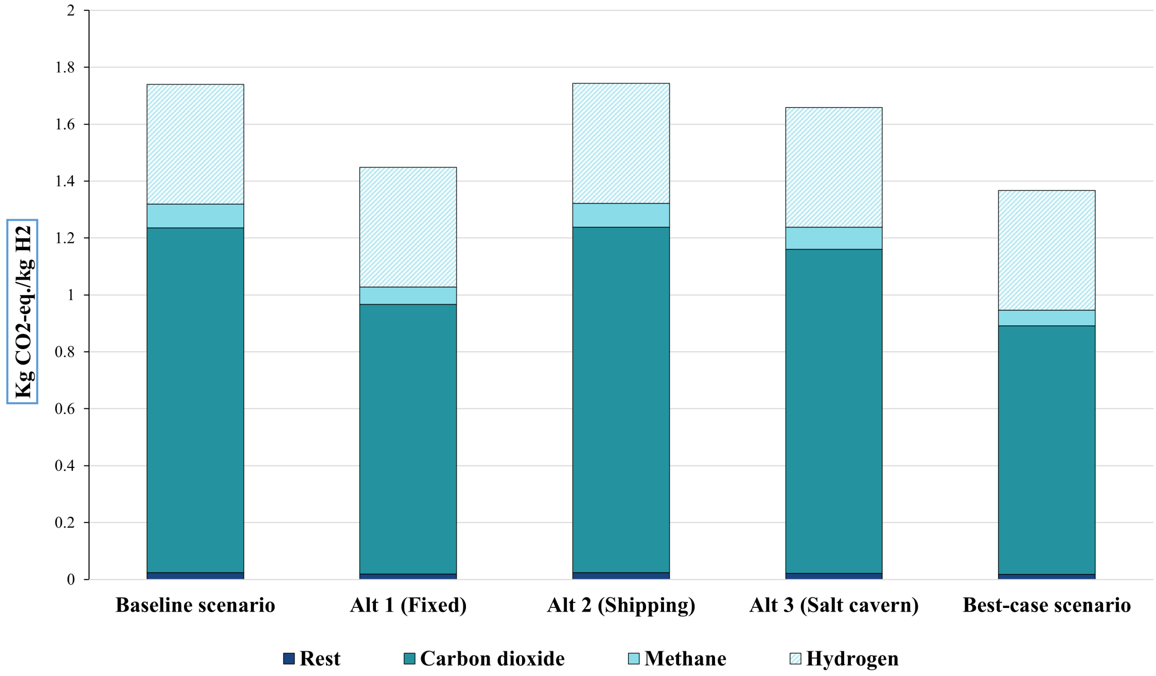

**Figure 3.2:** Emission including hydrogen leakage impact in the various scenarios. Results indicate a lower environmental impact for the cases of bottom-fixed turbines and salt cavern storage.

Regardless of the impact from hydrogen leakage, previous work has shown that green hydrogen is beneficial in terms of mitigated $CO_2$ emissions for all policy-relevant time horizons when compared to blue and grey hydrogen production. Blue and grey hydrogen production have the additional impact from potential methane and carbon dioxide leakages, resulting in a larger environmental impact [24].

The environmental impact from blue and grey hydrogen was supposed to be several times larger due to the additional GHG emissions. Depending on the technology utilized, $CO_2$ capture rate, $CH_4$ emission rate, etc., previous work [60] [61] [62] estimated the climate change impact of blue and grey hydrogen in the range of 1.5 - 5 kg $CO_2$-eq./kg $H_2$ and 8.5 - 11 kg $CO_2$-eq./kg $H_2$, respectively, and without addressing the risk associated with hydrogen leakage. The green offshore hydrogen production results showed a clear advantage compared to fossil-fueled hydrogen production, both with and without including the impact of hydrogen leakage.

The GWP100 metric has primarily been used as a measure of the relative impact of different GHGs. However, other alternative metrics utilizing different timeframes, such as GWP20, provide valuable insights and serve as important indicators. The GWP20 prioritizes and presents larger values for gases with a shorter lifetime. For example, for $CH_4$, which has a short lifetime, the GWP100 of 27 – 30 is much less than the GWP20 of 81 – 83 [63]. This will especially be the case for $H_2$, as the GWP20 is much larger than for 100 years. Studies have shown that this value is four to five times larger, in the range of 30 - 40 kg $CO_2$-eq./kg $H_2$ [23] [24] . Figure 3.3 shows the difference when comparing the baseline- and the best-case scenario for the two metrics, GWP100 and GWP20, when utilizing the values 8 and 35, respectively.

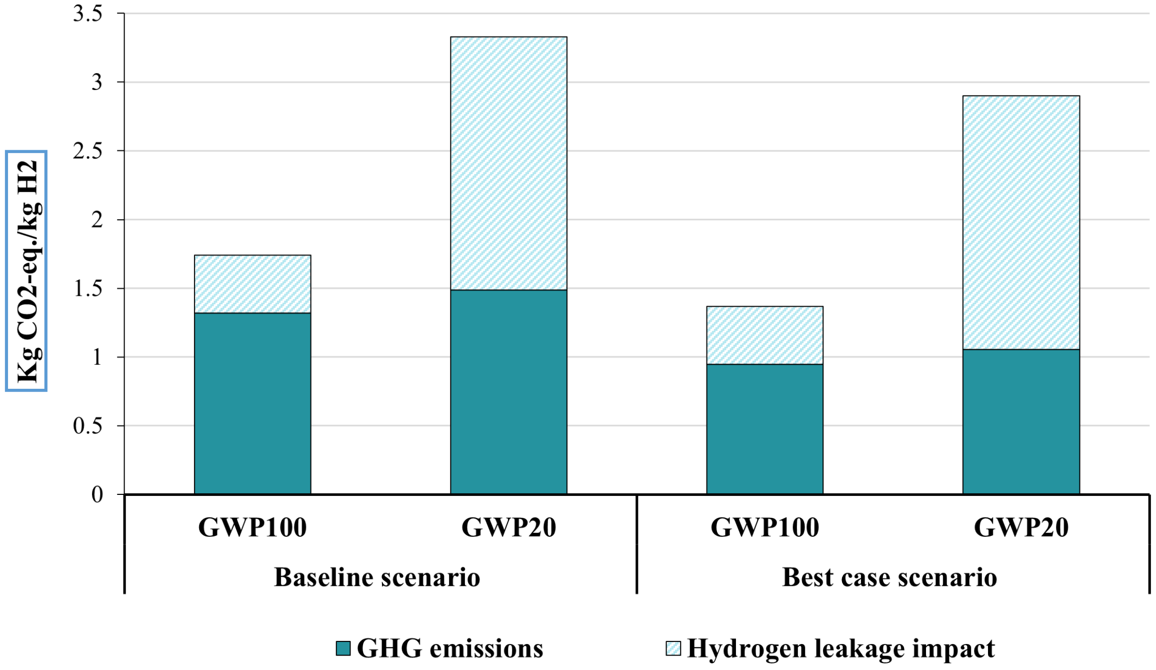

**Figure 3.3:** Emissions from baseline- and best-case scenario, comparing the GWP100 and GWP20 metrics. GHG emissions slightly rise, and the impact from hydrogen drastically increases for the GWP20 metric. These results are mainly due to the impact of short-lived gases such as hydrogen and methane ($CH_4$).

The results for GWP20 are much higher because hydrogen is a short-lived gas with an atmospheric lifetime of only a few years. However, even a 20-year time horizon is long for a gas that only lasts a few years in the atmosphere. Considering an even shorter time frame would therefore present an even higher potency relative to carbon dioxide. This decrease in relative cumulative radiative forcing over the years can be seen in Figure 1.1 in Section 1.2.1.

When examining findings concerning a previous LCA evaluating onshore windpower [19], the estimated results indicated a larger impact than the case for onshore production. This was a sensible finding as offshore turbines required much more materials for stability in structure to withstand harsher conditions. In contrast, the mentioned LCA focused explicitly on the production phase, excluding the transportation, storage, and distribution stages, which indicated a lower impact. Looking closer at this project case, offshore wind turbines and the platform was seen to have the largest impact in all the evaluated scenarios. Therefore, a broader focus was situated on the production stage and the impact of modifications through the alternative scenarios.

### 3.1.1 Offshore wind turbines

From the results, floating offshore wind turbines were observed to have a larger environmental impact than bottom-fixed turbines. One might have anticipated a divergent outcome due to a more invasive interference with the seabed for bottom-fixed turbines. However, derived from the compiled inventories in Section 2.2.2, a remarkably larger usage of steel was detected for the floating foundation compared to bottom-fixed foundations.

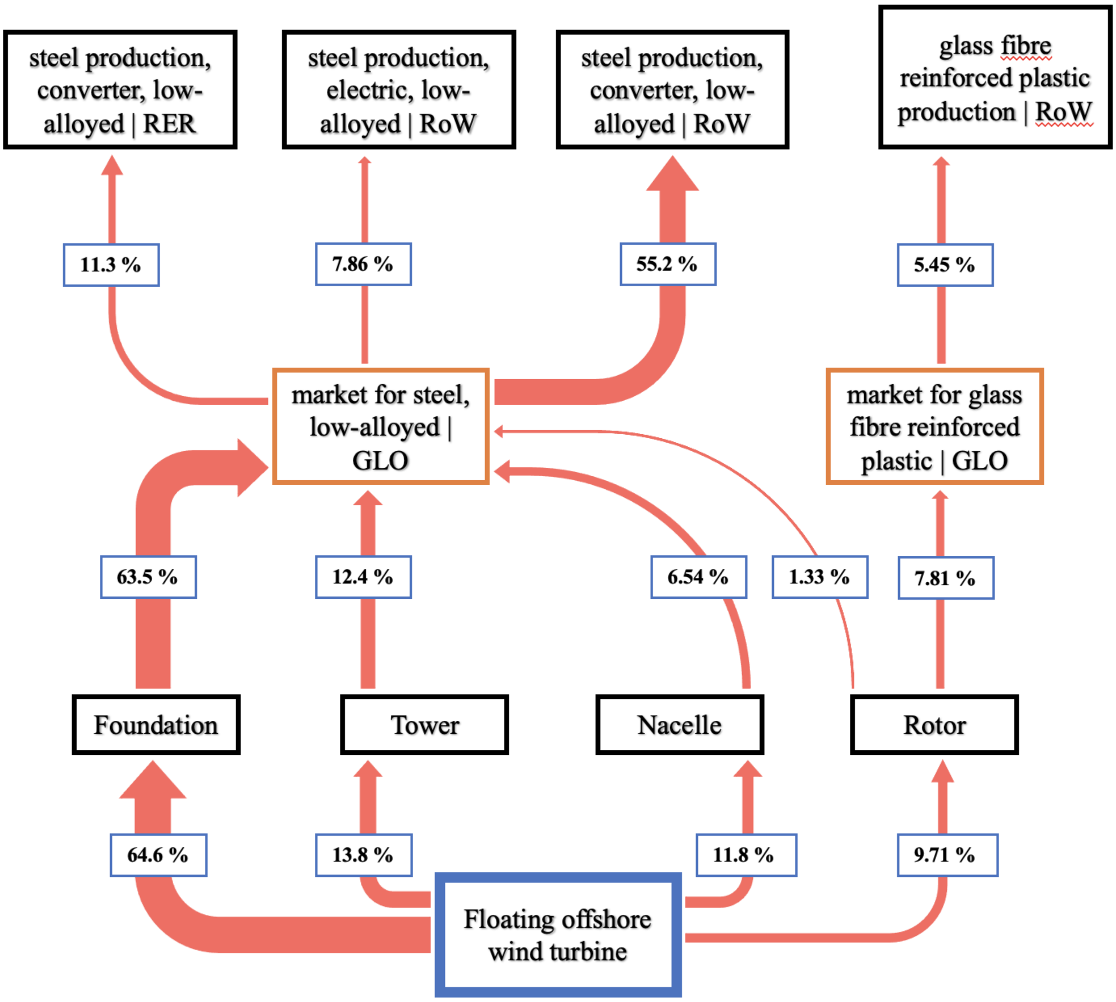

**Figure 3.4:** Sankey diagram showing the major environmental impact drivers for the floating offshore wind turbine. Steel production is responsible for the primary contribution of emissions, mainly due to production from converters from the rest of the world.

Reviewing a further breakdown of the floating offshore wind turbines, shown in the Sankey diagram in Figure 3.4, it can be seen that the foundation is accountable for close to 65%

of the turbine emissions. This is equivalent to around 35% of the system's total emissions. Depending on the chosen foundation technology, the total weight may vary. However, data used for calculations were based on an average, and the foundations were mainly made up of low-alloyed steel. This was also the case for the nacelle, rotor, and tower, resulting in steel production being responsible for around 84% of the total emissions from the offshore wind turbine.

Steel production is a complex process generally produced using either the converter process, also called the blast furnace-basic oxygen method, or the electric arc furnace method. When using a blast furnace, iron ore is melted down before being mixed with limestone and coke to produce pig iron. This process is energy-intensive and requires large amounts of fuel to maintain high temperatures. In contrast, the electric arc furnace involves melting recycled steel using electricity [64]. The carbon footprint of steel production can therefore vary depending on the method and energy source in the production process. The data for steel and other materials are based on the market activities in the Ecoinvent 3.8 database. A market activity refers to the combination of products or activities in a specific geographical region, considering trade between the producer and consumer, as well as any losses incurred during transportation [65]. Figure 3.5 shows a comparison of the different steel production methods.

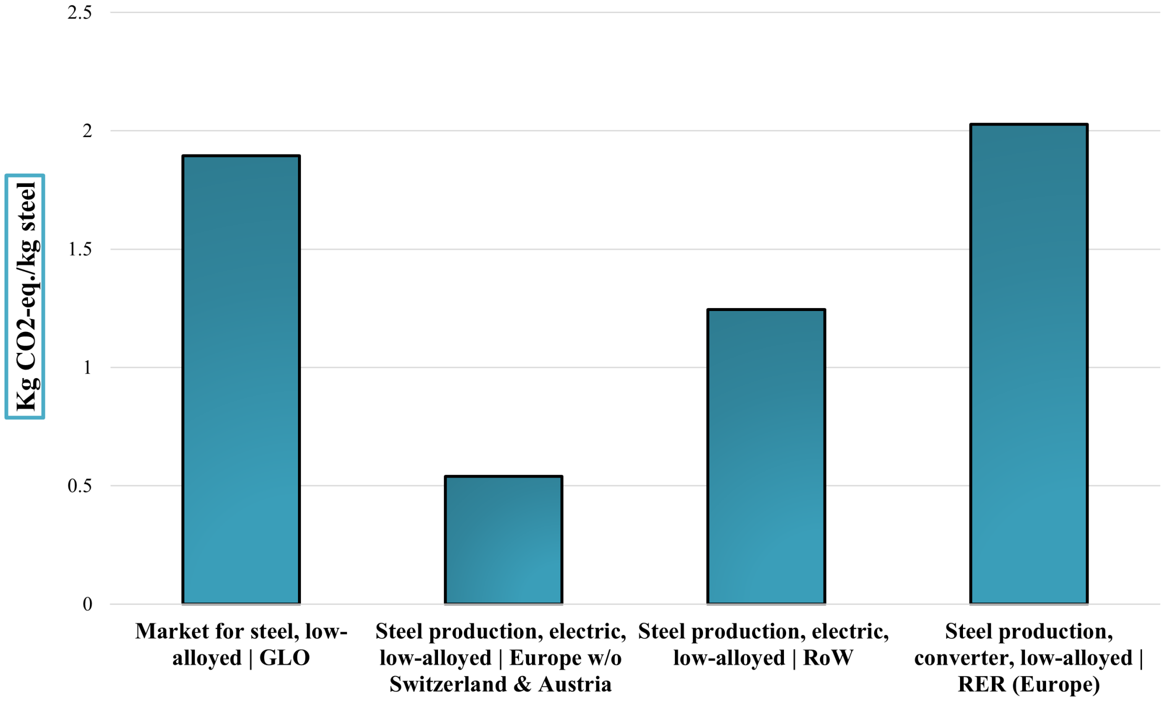

**Figure 3.5:** Comparison of the emissions from different steel production methods presented in kg $CO_2$ equivalents per kg of produced steel.

It was observed that the market for steel production had a considerably larger GWP than steel production from electric arc furnaces in Europe. According to IEA, the carbon footprint of steel was around 1.4 tons per produced ton of steel [66], which was a close estimate to the data from Ecoinvent. In the sensitivity analysis 3.3, the usage of electric arc furnaces from Europe for steel production was compared to the market value used in earlier cases.

Composite materials such as glass or carbon fiber are also commonly used in wind turbines, mainly in the rotor, due to their high strength-to-weight ratio. This can also be derived from Figure 3.4, with around 8% of the total emissions arising from glass fiber production. Both glass and carbon fiber production processes are energy-intensive, which was the reason for the distinct impact. As the impact mostly was based on energy efficiency and energy source, measures such as using green electricity and recycling materials may be viable mitigation options. This was determined as a general takeaway from both the estimated results and previous studies. Material consumption in the production phase is a main contributor to GHG emissions, primarily due to extraction and raw material processing, which is deeply dependent on fossil fuels.

### 3.1.2 Hydrogen production

Moving further through the supply chain to hydrogen production, it was observed that the main impact originated from the platform. The results showed that steel was the most common material used to construct the platform, accounting for closer to half of the emissions. There was also a high demand for electricity and diesel, accounting for around 44% of the total emissions of the platform. The platform was based on data from a natural gas platform from the Ecoinvent 3.8 database, which might be a possible reason why the emissions are so high. This data was related to the Odin platform, which is a gas installation with drilling equipment and living quarters on top of a steel jacket. The energy and water requirements were collected from 1980 data, and the material requirements were reported in 1996. Therefore, the impact from this platform might be outdated, resulting in a larger impact than for a new platform specifically designed for hydrogen production. The results will still give an indication of material consumption and total emissions, but this information must be taken into consideration when evaluating the impact of the offshore platform.

### 3.1.3 Hydrogen storage

As seen in the compiled inventories based on Premise [52], storage tanks are mainly made up of carbon fiber. From the previous discussion, carbon fiber production was recognized as an energy-intense process, and the amount of material was a deciding factor in this stage in the value chain. Results showed that one day of hydrogen production gave an output of around 24 780 kg for storage when estimating a 2.5% hydrogen loss in previous stages. This was an exceptionally large amount of hydrogen to store, requiring a lot of space, resulting in a colossal storage tank facility with the following emissions. Such a large-scale hydrogen production project was determined unrealistic based on the achieved results. On the other hand, salt caverns showed a huge potential for storing hydrogen. As the materials for the well system and riser were the only components needed for storage, this had a significantly lesser impact. The storage capacity of salt caverns ranged from 100 000 $m^3$ to 1 000 000 $m^3$ [67]. With a pressure of 200 bar and volumetric density of around 15.6 kg/$m^3$, calculations declared that one month of storage from the defined system required less than 50 000 $m^3$. This implied that the capacity limitations of storage tanks could be solved by using underground salt cavern storage. Previous literature reviewed also determined salt caverns as a favorable option due to the low volumetric density resulting in capacity limitations when assessing compressed hydrogen storage. Figure 3.6 shows the difference between one day of storage in storage tanks versus one unit salt cavern with the capacity of storing at least one month.

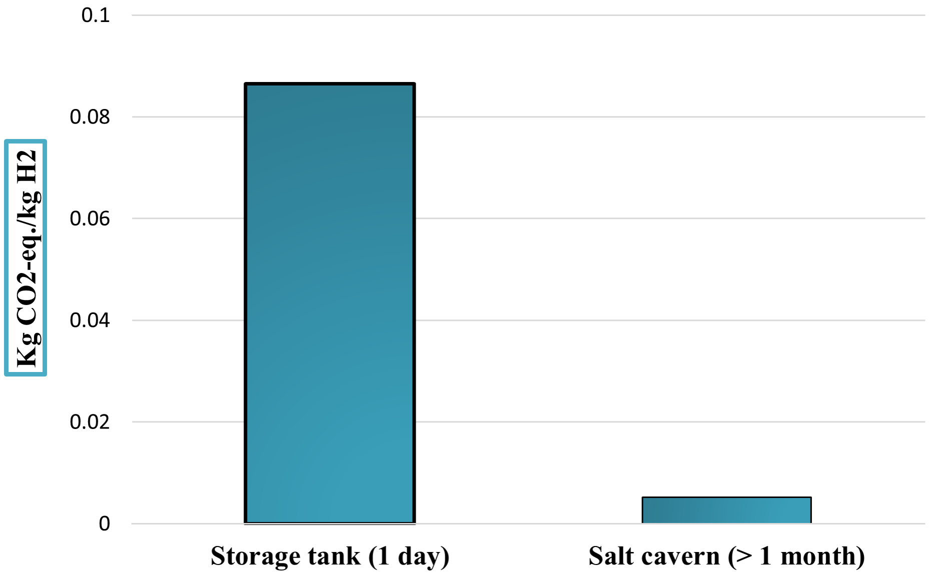

**Figure 3.6:** Comparison of the emissions from different storage alternatives presented in kg $CO_2$ equivalents per kg delivered $H_2$.

However, there are limitations and challenges associated with underground hydrogen storage in salt caverns. These major challenges relate to the fluid flow behavior of hydrogen in subsurface reservoirs, geochemical reactions caused by hydrogen injection, biotic reactions caused by excess hydrogen, and the geomechanical response of the subsurface to hydrogen storage [68]. To elaborate, reactions may occur when hydrogen is injected into an underground formation due to the changing chemical equilibrium between the rock minerals, pore water, gases, ions, and bacteria. This results in abiotic (chemical) and biotic (bacterial) processes, potentially leading to significant hydrogen losses, hydrogen contamination, and changes in the mineral composition that can impact the injectivity, promoting leakage [69]. As interpreted from the results mentioned earlier in this section, hydrogen loss and leakage has a severe environmental impact. Salt caverns are also limited in geographical capacity as they can only be formed in a few areas where there are natural salt deposits [69]. In other words, this means that the potential for utilization of salt caverns is limited when implementing hydrogen production on a gigatonne scale.

### 3.1.4 Hydrogen distribution

For the distribution, results showed that the overall difference in emission for the two cases of truck and shipping were almost analogous. Shipping distribution was estimated to have a slightly larger emission impact, as shown in Figure 3.7. This is the opposite result of what one would expect.

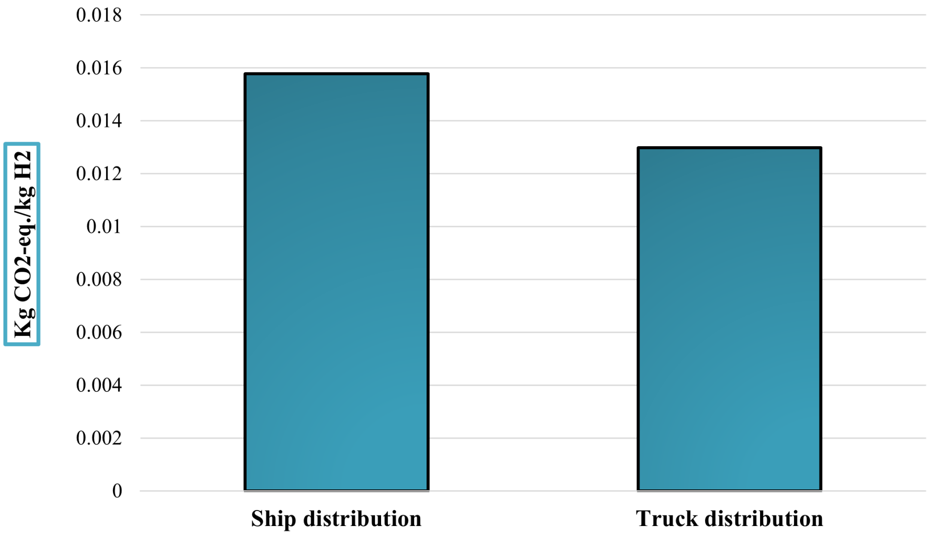

**Figure 3.7:** Comparison of the emissions from different distribution alternatives presented in kg $CO_2$ equivalents per kg delivered $H_2$.

Shipping distribution was anticipated to have a greater capacity for transporting hydrogen compared to truck distribution. Consequently, the use of shipping for hydrogen transportation would entail fewer roundtrips, thereby reducing the overall environmental impact associated with transportation. Nevertheless, it is important to note that the truck distribution utilized an unspecified lorry from the Ecoinvent 3.8 database, whereas the shipping distribution utilized a natural gas tanker ship. To accurately compare the two modes of distribution, a conversion factor of 16, derived in Section 2.2.2, was applied to the shipping distribution volume to account for the transformation from natural gas to hydrogen. This led to a much larger impact on the shipping distribution and showed a limitation in the Ecoinvent 3.8 database when utilizing ton-kilometer units for the two distribution options. However, the difference in climate impact is relatively small when divided by the total produced hydrogen.

### 3.1.5 Limitations

There were several limitations that could have affected the obtained results. As stated in Section 2.2.3, due to technology immaturity, the data was chosen based on availability and experience. Hence, prospective LCA was not accounted for, which may have resulted in some impacts declining. A prospective LCA is a forward-looking LCA, namely, which specifically looks at the future environmental impacts related to technologies and their products [70]. A lower total weight of materials and an updated material distribution relying less on materials associated with high emissions could be expected for a prospective LCA. It would also be reasonable to expect parts of the extraction and processing of materials to be less dependent on fossil fuel due to the replacement of renewable sources, resulting in fewer emissions.

A further breakdown of all scenarios, including Sankey diagrams for the components in the baseline scenario and tables showing the impact of each component and main contributing activities, is included in the Appendix A for further review.

## 3.2 Other impact categories

Table 3.3 summarizes the results from the other impact categories included in ReCiPe Midpoint (H). As observed from the results, most cases showed a larger impact for the baseline and shipping scenario, with the production stage responsible for most categories' main impact.

It is worth mentioning the impact of copper in several of the impact categories, especially in the categories assessing human toxicity, freshwater-, marine-, and terrestrial ecotoxicity. The production of copper is a key factor in the human toxicity potential, which calculates an index that reflects the potential harm of a unit of chemical released into the environment [71], as large amounts of copper may be toxic for humans. When copper ends up in the soil, it strongly attaches to the present organic matter and minerals. Its inherent stability prevents it from breaking down in the environment, leading to potential accumulation in plants and animals. This poses a serious threat to agricultural productivity, as copper can interrupt the activity in the soil due to negatively influencing the activity of microorganisms and earthworms, thus slowing down the decomposition of organic matter [72]. Concentrations of copper may be absorbed by animals and further absorbed by humans, leading to copper toxicity. Results showed that the component responsible for the main proportion of copper was the nacelle in the wind turbine. The copper material distribution was considerably larger in the floating wind turbine compared to the bottom-fixed, resulting in a larger impact for the scenarios using floating technology.

Depletion is a measure of resource scarcity. Fossil depletion and metal depletion refer to the diminishing future availability of fossil fuels and metals resulting from their extraction for fuel,

**Table 3.3:** LCA results, all impact categories included in ReCiPe Midpoint (H)

| **Impact categories** | **Baseline** | **Alt 1** | **Alt 2** | **Alt 3** | **Best-case** |
|---|---|---|---|---|---|
| Agricultural land occupation [m$^2$-year] | 0.04097 | 0.03179 | 0.04093 | 0.03539 | 0.02621 |
| Climate change [kg CO$_2$-eq./kg H$_2$] | 1.31953 | 1.02778 | 1.32234 | 1.23812 | 0.94637 |
| Fossil depletion [kg oil-eq.] | 0.35712 | 0.27450 | 0.35725 | 0.33387 | 0.25124 |
| Freshwater ecotoxicity [kg 1,4-DcB-eq.] | 0.16084 | 0.06836 | 0.16081 | 0.15898 | 0.06650 |
| Freshwater eutrophication [kg P-eq.] | 0.00076 | 0.00044 | 0.00076 | 0.00073 | 0.00041 |
| Human toxicity [kg 1,4-DCB-eq.] | 1.25338 | 0.63915 | 1.25036 | 1.22568 | 0.61146 |
| Ionising radiation [kg U235-eq.] | 0.07793 | 0.06268 | 0.07780 | 0.07117 | 0.05592 |
| Marine ecotoxicity [kg 1,4-DCB-eq.] | 0.15018 | 0.06609 | 0.15012 | 0.14853 | 0.06444 |
| Marine eutrophication [kg N-eq.] | 0.00200 | 0.00162 | 0.00210 | 0.00192 | 0.00154 |
| Metal depletion [kg Fe-eq.] | 1.35144 | 0.76403 | 1.35150 | 1.15475 | 0.76734 |
| Natural land transformation [m$^2$] | 0.00023 | 0.00019 | 0.00023 | 0.00022 | 0.00018 |
| Ozone depletion [kg CFC-11-eq.] | 7.42E-08 | 5.72E-08 | 7.43E-08 | 7.22E-08 | 5.52E-08 |
| Particulate matter formation [kg PM10-eq.] | 0.00498 | 0.00353 | 0.00508 | 0.00480 | 0.00336 |
| Photochemical oxidant formation [kg NMVOC] | 0.00714 | 0.00548 | 0.00742 | 0.00692 | 0.00525 |
| Terrestrial acidification [kg SO2-eq.] | 0.00844 | 0.00600 | 0.00877 | 0.00807 | 0.00564 |
| Terrestrial ecotoxicity [kg 1,4-DCB-eq.] | 0.00021 | 0.00014 | 0.00020 | 0.00021 | 0.00014 |
| Urban land occupation [m$^2$-year] | 0.02907 | 0.02082 | 0.02817 | 0.02847 | 0.02022 |
| Water depletion [m$^3$] | 0.00574 | 0.00498 | 0.00573 | 0.00552 | 0.00477 |

energy use, and material use [73]. A clear difference in the fossil- and metal depletion for each of the cases, with a lower value for alternative scenario 1 (bottom-fixed turbines), was observed from the results. A further breakdown showed that this was mainly due to the production of steel from the foundation of the wind turbine and platform. Steel production is often a main contributor when assessing most of the other impact categories. This added additional weight to the implication of the importance of steel production, which was further assessed in the sensitivity analysis 3.3.

## 3.3 Sensitivity analysis

This section reviewed the performed sensitivity analysis, mainly focusing on two aspects, hydrogen loss, and steel production. To understand how crucial these factors were to the results, both the percentage of hydrogen leakage through losses and change production methods for steel production were evaluated through varying values.

### 3.3.1 Hydrogen leakage rates

The hydrogen leakage rate was estimated to be around 5% for previous cases, based on an assumption from the literature review 1.2. Figure 3.8 presents six cases evaluating hydrogen leakage in the range of 0% to 20% and shows how changes in the hydrogen leakage rate can affect the total GWP impact for the baseline scenario.

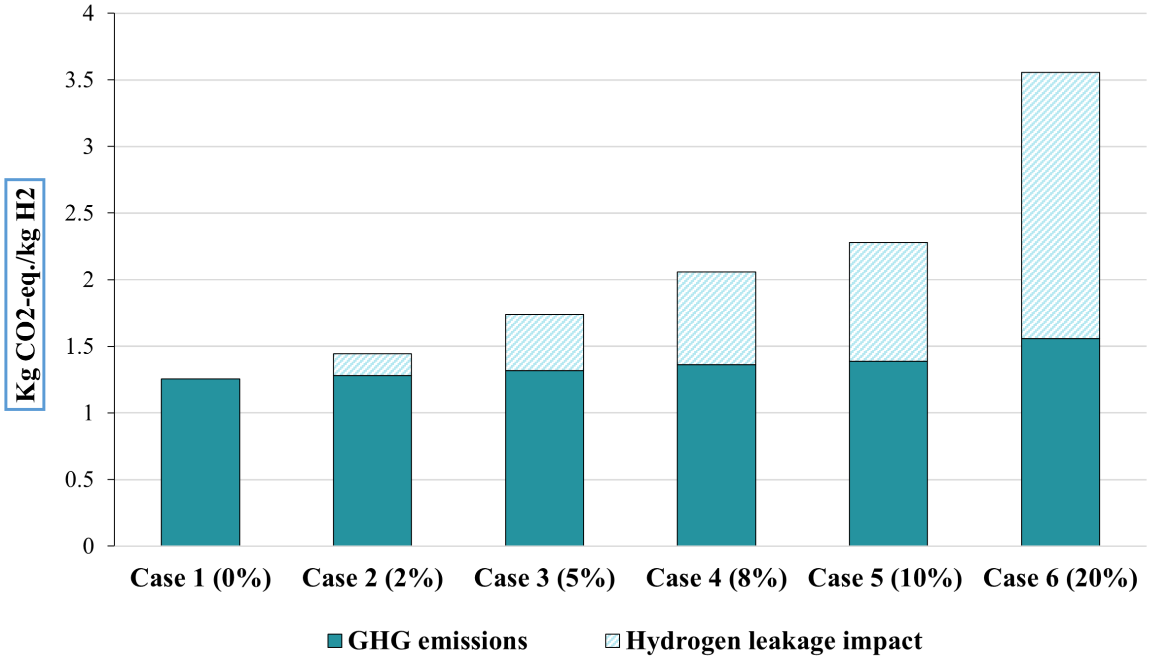

**Figure 3.8:** Comparison of the GHG emissions from different hydrogen leakage rates in the baseline scenario. Results indicate a distinct increase in kg $CO_2$-eq./kg $H_2$ for higher leakage rates.

Results showed that a larger percentage of hydrogen leakage resulted in a considerable environmental impact. With the unit kg $CO_2$-eq./kg $H_2$, the results from the sensitivity analysis showed 1.26 for 0%, 1.44 for 2%, 1.74 for 5%, 2.06 for 8%, 2.28 for 10%, and 3.56 for 20%. A 20% leakage rate equaled closer to 56% of the total emissions. This revealed a crucial limitation for offshore hydrogen production and hydrogen projects in general.

As mentioned in Section 1.2, hydrogen's small molecule size, low molecular weight, high diffusivity, and low viscosity make it challenging to contain, and it can, therefore, easily result in leakage from the infrastructure through the value chain. Not only does hydrogen leakage have an environmental impact, but it may also lead to hydrogen embrittlement in materials and system components. Hydrogen embrittlement refers to the mechanical damage of a metal causing loss in ductility and tensile strength [74]. This may result in a larger amount of leakage and a higher need for maintenance. Thus, detecting and preventing hydrogen leakage is essential for ongoing and future hydrogen projects. To help minimize hydrogen's warming effects, a list of actions, including conducting more research, accurately measuring leakage, using climate metrics, including the likelihood of hydrogen leakage and its impacts, and identifying leakage mitigation measures and best practices, must be applied [20]. To maximize the mitigation of climate impacts during a large-scale transition to a hydrogen economy, reducing the leakage rate of hydrogen and increasing the green hydrogen production pathways are crucial.

### 3.3.2 Steel production methods

The process of steel production is highly energy-intensive. However, the carbon footprint for the process varies largely based on the production method and energy source. Figure 3.9 presents the GWP100 impact of our baseline scenario for offshore hydrogen production, considering the different production technologies for only the foundation. The first case was based on the average technology available in the market [51], which was the value used throughout this project. The second and third cases used electric arc furnace technology, reliant on electricity from Europe, and blast furnace technology. This technology change was only applied to the offshore wind turbine as the preeminent material here was steel, and the main impact resided from this stage. Note that hydrogen emission was set constant due to no assumed changes in the hydrogen leakage rate. This was determined a critical place to mitigate emissions due to the significant impact of the method and energy source used for steel production. By improving energy efficiency through implementing measures such as waste heat recovery and optimizing the production process, the environmental impact of steel may be lowered. Using green electricity from wind, solar, or hydropower for production, reducing waste, and recycling the materials are also measures to reduce the negative environmental impact.

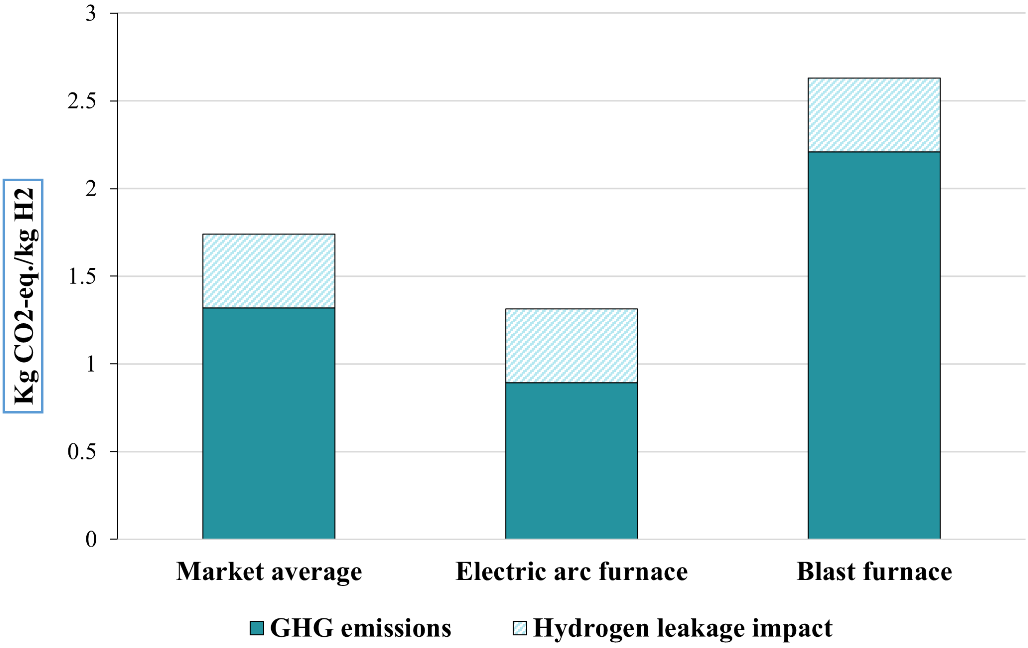

**Figure 3.9:** Comparison of the emissions from different alternatives of steel production in the foundation for the baseline scenario, based on values from Ecoinvent [51]. Results indicate the total environmental impact for the three evaluated production methods when only adapting the methods in the foundation.

### 3.4 Techno-economic aspects

Regardless of offshore hydrogen production's environmental impact, the economic aspect is an extremely decisive factor when assessing from an investment point of view. Therefore, a general understanding of the costs associated with such a project was essential.

Upon a closer examination of the production costs associated with the various types of hydrogen, namely green, blue, and grey, it became evident that fossil-based technologies incurred significantly lower costs. There were wide ranges among all the calculated hydrogen costs for the different production methods due to diverse assumptions regarding possible operating hours and fossil fuel or electricity costs depending on the region of operations. It was also important to keep in mind that grey hydrogen currently is produced at a GW scale, whereas green hydrogen is still distributed with a much smaller capacity [75]. From relevant studies, one observed that production costs for grey hydrogen were in the range of 0.9 to 3.2 US$/kg $H_2$, and blue hydrogen 1.5 to 2.9 US$/kg $H_2$. Conversely, green hydrogen was estimated to have a production cost 2 - 3 times larger in the range of 3.0 to 7.5 US$/kg $H_2$ [76]. Another study specifically assessing offshore hydrogen production calculated the production costs to be higher, around 13.81 to 13.85 US$/kg $H_2$ [77]. This showed the economic limitation of an offshore hydrogen production project, emphasizing the potential need for governmental subsidy and support schemes.

# 4 Conclusion

The objective of this study was to explore the potential and possibilities for offshore hydrogen production from offshore wind farms along the Norwegian coast. Through a review of relevant literature and LCA, this project aimed to determine the environmental impact of offshore hydrogen production and identify the main contributors associated with emissions. Furthermore, the study aimed to assess and discuss the environmental impact resulting from hydrogen leakage.

Results from the baseline scenario showed an estimated climate footprint of around 1.32 kg $CO_2$-eq./kg $H_2$ primarily due to carbon dioxide and methane, when excluding the impact from hydrogen leakage. This was determined as a sensible result due to the correspondence with existing studies, which also showed a global warming potential in the range of 1 - 2 kg $CO_2$-eq./kg $H_2$. A closer inspection of scenarios evaluated in the LCA revealed the most impactful alterations resulting in a best-case scenario integrating the favorable environmental technologies, including bottom-fixed offshore wind turbines, salt cavern storage, and truck distribution. This led to a decrease in emissions, resulting in 0.95 kg $CO_2$-eq./kg $H_2$ for the best-case scenario when excluding the impact from hydrogen leakage.

A further breakdown concluded that the offshore wind turbines and platform were responsible for the main environmental impact. These components were mainly made of steel and represented a considerable proportion of the system's total weight, resulting in a more significant global warming potential. The analysis revealed steel production as a preeminent emission source dependent on the production method. The analyzed cases consisted of an average technology available in the market, combining values from several production methods, resulting in steel production being responsible for around 84% of the floating turbine's total emissions. The amount of steel utilized in the different offshore turbine technologies was also derived as the reason for a larger environmental impact from the floating foundation compared to the bottom-fixed foundation. Obtained results and previous studies concluded that material consumption, mainly steel, in the production phase contributed to GHG emissions, primarily due to extraction and raw material processing, which is deeply dependent on fossil fuels. Therefore, measures such as utilizing recycled materials and green electricity for material extraction and production are viable mitigation options.

Hydrogen losses were estimated to have a substantial environmental impact when leaking into the atmosphere. Due to its atmospheric oxidation reactions, hydrogen contributes to climate change by increasing concentrations of other GHGs. The GWP100 value was set to be eight times relative to carbon dioxide emissions, resulting in 0.42 kg $CO_2$-eq./kg $H_2$ for all scenarios based on a 5% hydrogen leakage rate. This resulted in a total global warming potential of 1.74

kg $CO_2$-eq./kg $H_2$ for the baseline scenario, showing the immense environmental impact. This perception was further strengthened in the sensitivity analysis when altering the leakage rates for the baseline scenario in the range of 0% to 20%, giving even larger values for higher leakage rates.

Compared to blue and grey hydrogen, green hydrogen had a production cost several times larger in the range of 3.0 to 7.5 US$/kg H2 and around 13.81 to 13.85 US$/kg H2 for the offshore case. However, green hydrogen was beneficial in terms of mitigated $CO_2$ emissions for all policy-relevant time horizons due to the additional environmental impact of potential methane and carbon dioxide leakages. This compares the beneficial environmental impact to the economic limitation of an offshore hydrogen production project, emphasizing the potential need for governmental subsidy and support schemes. In conclusion, with support from the government, Norway showed promising potential for offshore hydrogen production. However, achieving maximum climate impact reduction during a large-scale transition to a hydrogen economy necessitates both the reduction of hydrogen leakage rates and the increased production of green hydrogen through the utilization of sustainable material production.

## 4.1 Further work

Considering the limitations and potential sources of error, further work is recommended to enhance the analysis. Since offshore hydrogen production is in the developmental stage, it is necessary to constantly update input data, particularly for hydrogen-specific components such as hydrogen platform, pipeline, and storage. Furthermore, given the limitations associated with hydrogen storage, there is a pressing need for a more comprehensive technical assessment when evaluating the possibilities of salt caverns along the Norwegian coast.

To extend the research and achieve a more comprehensive assessment, an inclusion of more stages is recommended in the LCA to gain a broader and more realistic perspective. It might also be interesting to expand the research to include a prospective LCA for future investigations. Incorporating anticipated material consumption and distribution in offshore hydrogen production for future scenarios would elevate the analysis to a higher level.

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# A Appendix

## A.1 Additonal results all scenarios

The GWP100 impact for each of the scenarios is included in Table A.1, showing the contribution from each component throughout the value chain.

**Table A.1:** Result for components in all scenarios, functional unit [kg $CO_2$-eq./kg $H_2$]

| **Components** | **Baseline** | **Alt 1** | **Alt 2** | **Alt 3** | **Best-case** |
|---|---|---|---|---|---|
| Offshore wind turbine | 0.712 | 0.401 | 0.712 | 0.712 | 0.401 |
| Platform | 0.326 | 0.326 | 0.326 | 0.326 | 0.326 |
| Electrolyzer | 0.071 | 0.071 | 0.071 | 0.071 | 0.071 |
| Compression and storage | 0.088 | 0.088 | 0.088 | 0.007 | 0.007 |
| Pipeline | 0.075 | 0.075 | 0.075 | 0.075 | 0.075 |
| Distribution | 0.013 | 0.013 | 0.016 | 0.013 | 0.013 |
| Offshore installation | 0.035 | 0.053 | 0.035 | 0.035 | 0.053 |
| **Total ex. hydrogen leakage** | **1.320** | **1.028** | **1.322** | **1.238** | **0.946** |
| Hydrogen leakage impact | 0.421 | 0.421 | 0.421 | 0.421 | 0.421 |
| **Total incl. hydrogen leakage impact** | **1.741** | **1.449** | **1.743** | **1.659** | **1.367** |

Table A.2 includes a further breakdown of the main contributing activities for all the scenarios, showing the environmental impact with the unit kg $CO_2$-eq./kg $H_2$.

**Table A.2:** Result for contributing activities for all scenarios, functional unit [kg $CO_2$-eq./kg $H_2$]

| **Activity** | **Baseline** | **Alt 1** | **Alt 2** | **Alt 3** | **Best-case** |
|---|---|---|---|---|---|
| Pig iron production | 0.226 | 0.124 | 0.226 | 0.226 | 0.124 |
| Electricity production, hard coal | 0.028 | 0.026 | 0.028 | 0.027 | 0.025 |
| Heat production, at hard coal industrial furnace | 0.083 | 0.066 | 0.083 | 0.063 | 0.047 |
| Iron sinter production | 0.057 | 0.031 | 0.057 | 0.057 | 0.032 |
| Hard coal mine operation and preparation | 0.049 | 0.034 | 0.049 | 0.046 | 0.031 |
| Diesel, burned in burning machine | 0.065 | 0.061 | 0.064 | 0.065 | 0.061 |
| Nylon production, glass-filled | 0.033 | 0.037 | 0.033 | 0.033 | 0.036 |
| Offshore installation fixed (diesel and HFO) | 0.000 | 0.053 | 0.000 | 0.000 | 0.053 |
| Offshore installation floating (diesel and HFO) | 0.035 | 0.000 | 0.035 | 0.035 | 0.000 |
| Clinker production | 0.000 | 0.028 | 0.000 | 0.000 | 0.028 |
| Rest | 0.745 | 0.567 | 0.748 | 0.687 | 0.510 |

## A.2 Sankey diagrams

Simplified Sankey diagrams of the main components contributing to high emissions rates are shown in Figure A.1, A.2, A.3, and A.4. Note that the Sankey diagrams only show the largest contributing flows and the percentage will, therefore, not sum up to 100 % everywhere. The figures are based on results from the LCA.

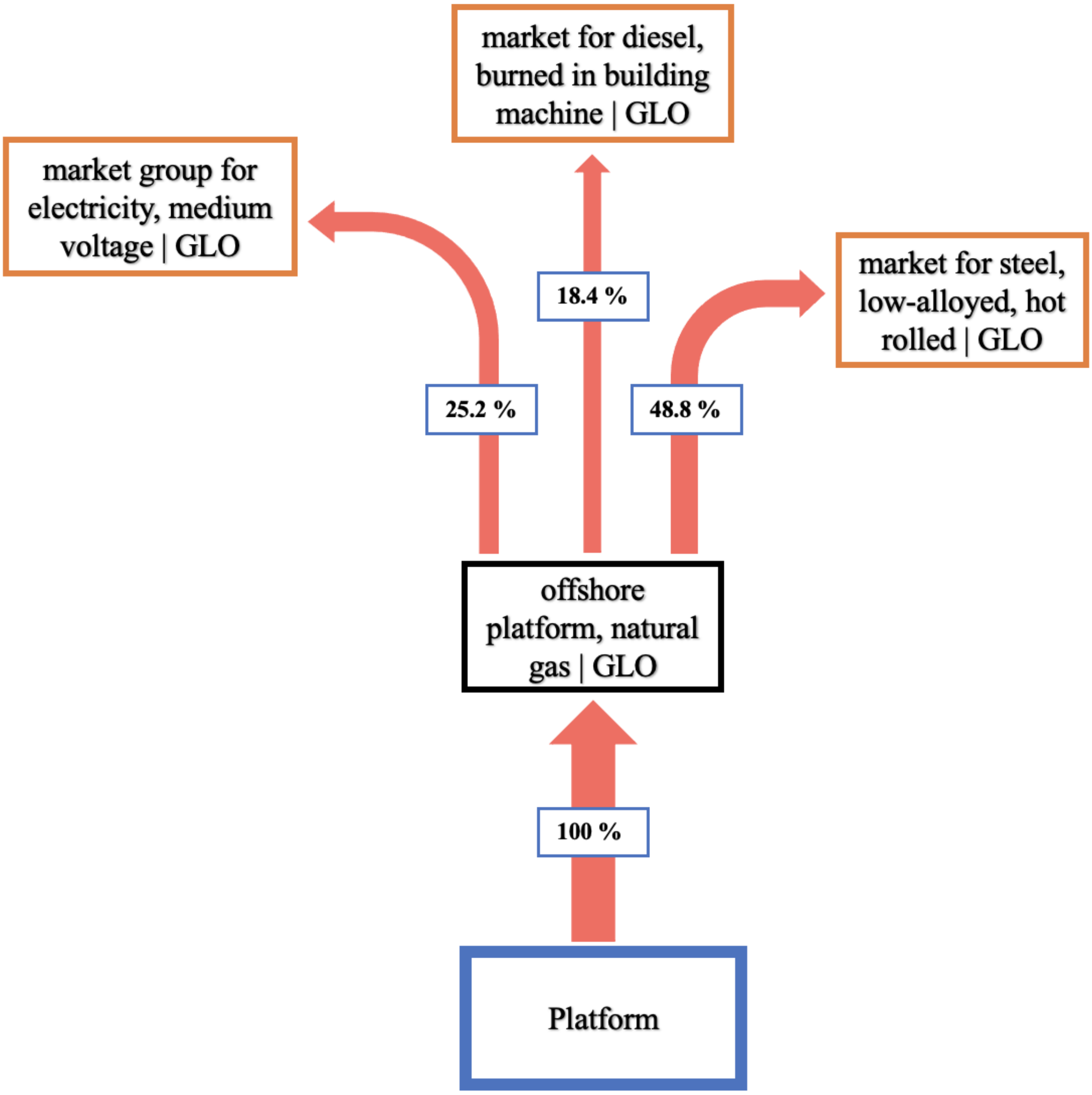

**Figure A.1:** Sankey diagram showing major environmental impact drivers for platform

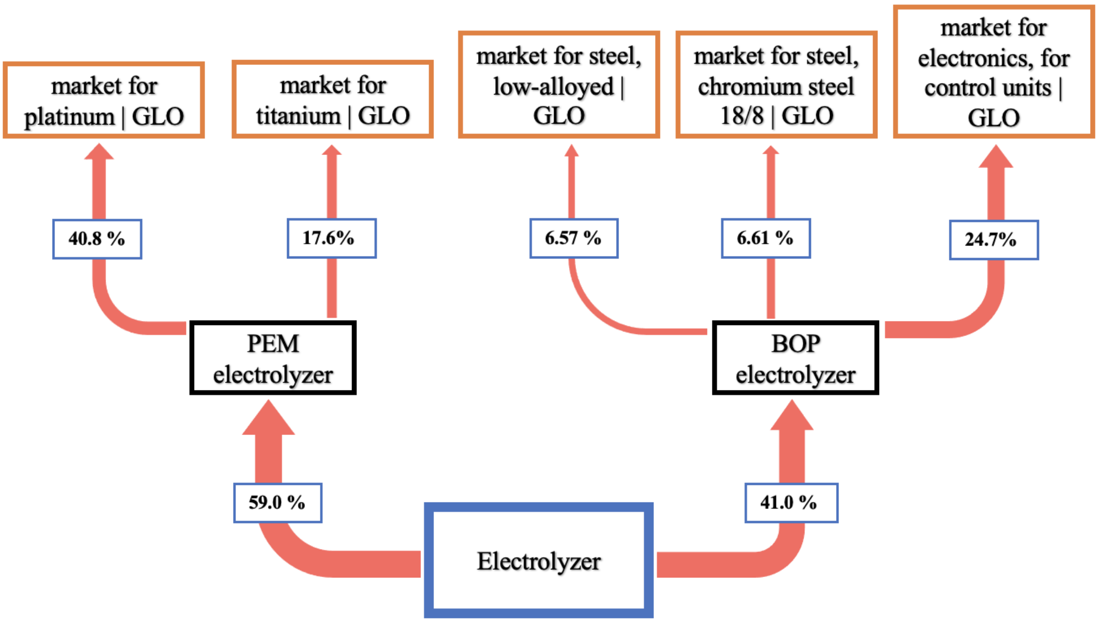

**Figure A.2:** Sankey diagram showing major environmental impact drivers for electrolyzers

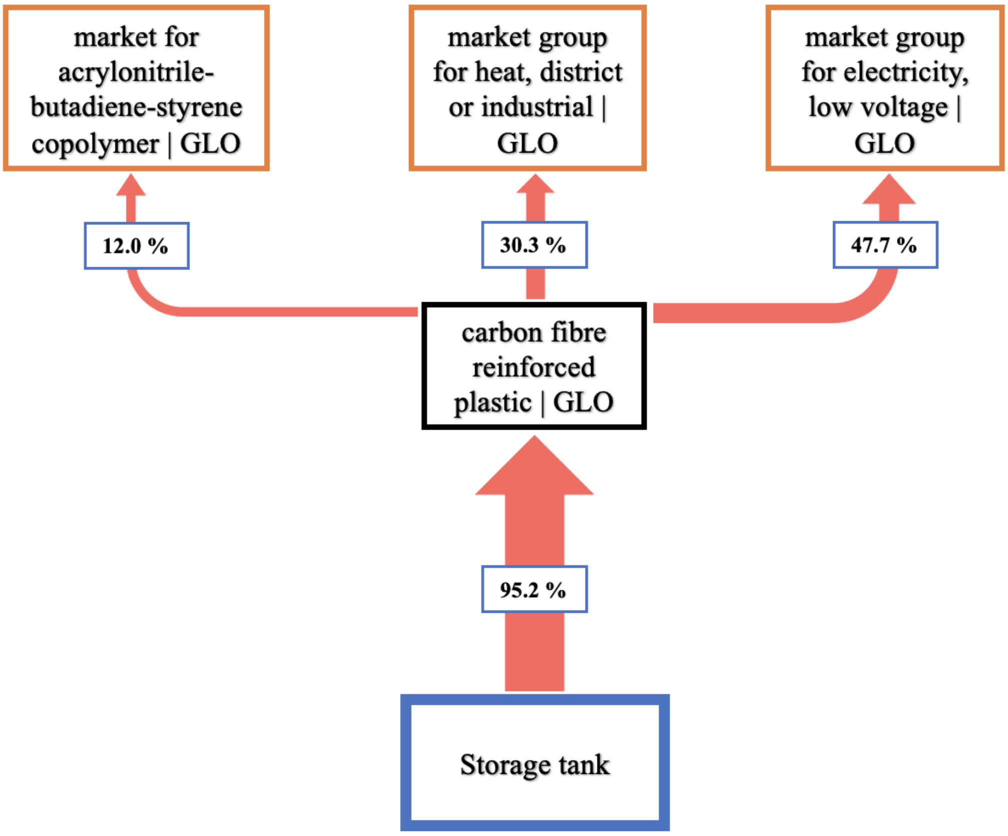

**Figure A.3:** Sankey diagram showing major environmental impact drivers for storage tanks

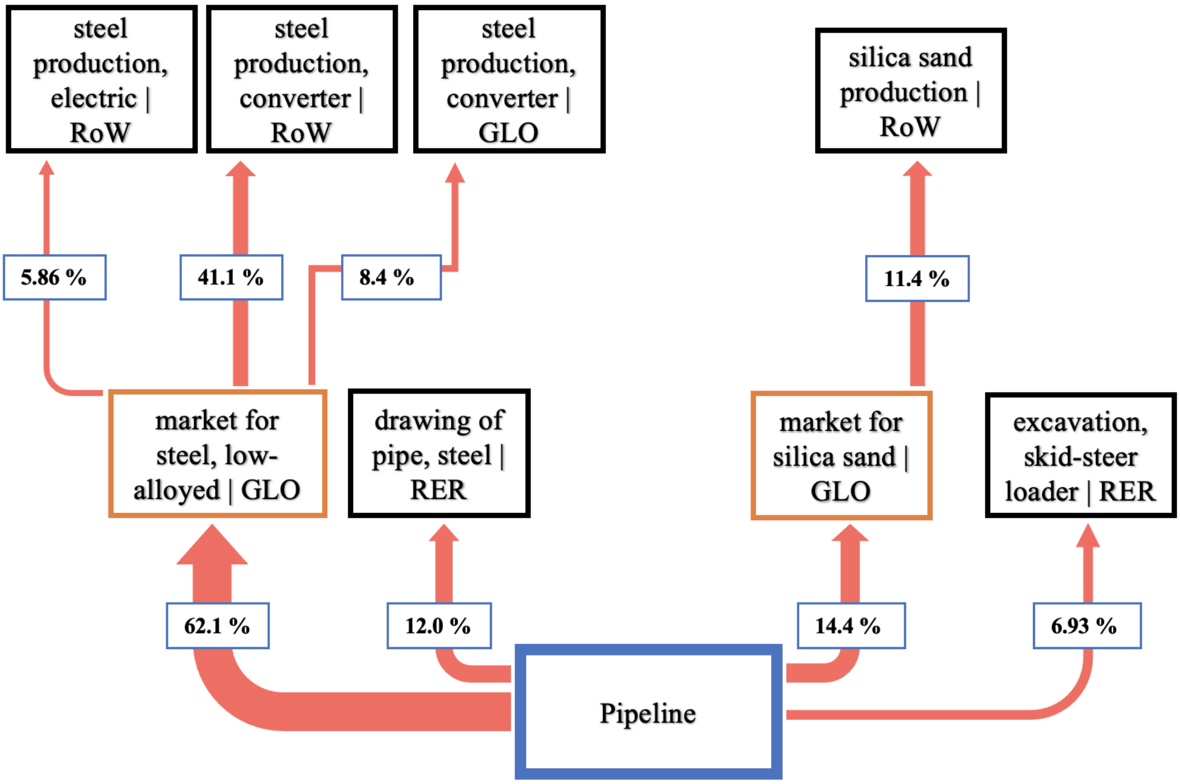

**Figure A.4:** Sankey diagram showing major environmental impact drivers for pipeline

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