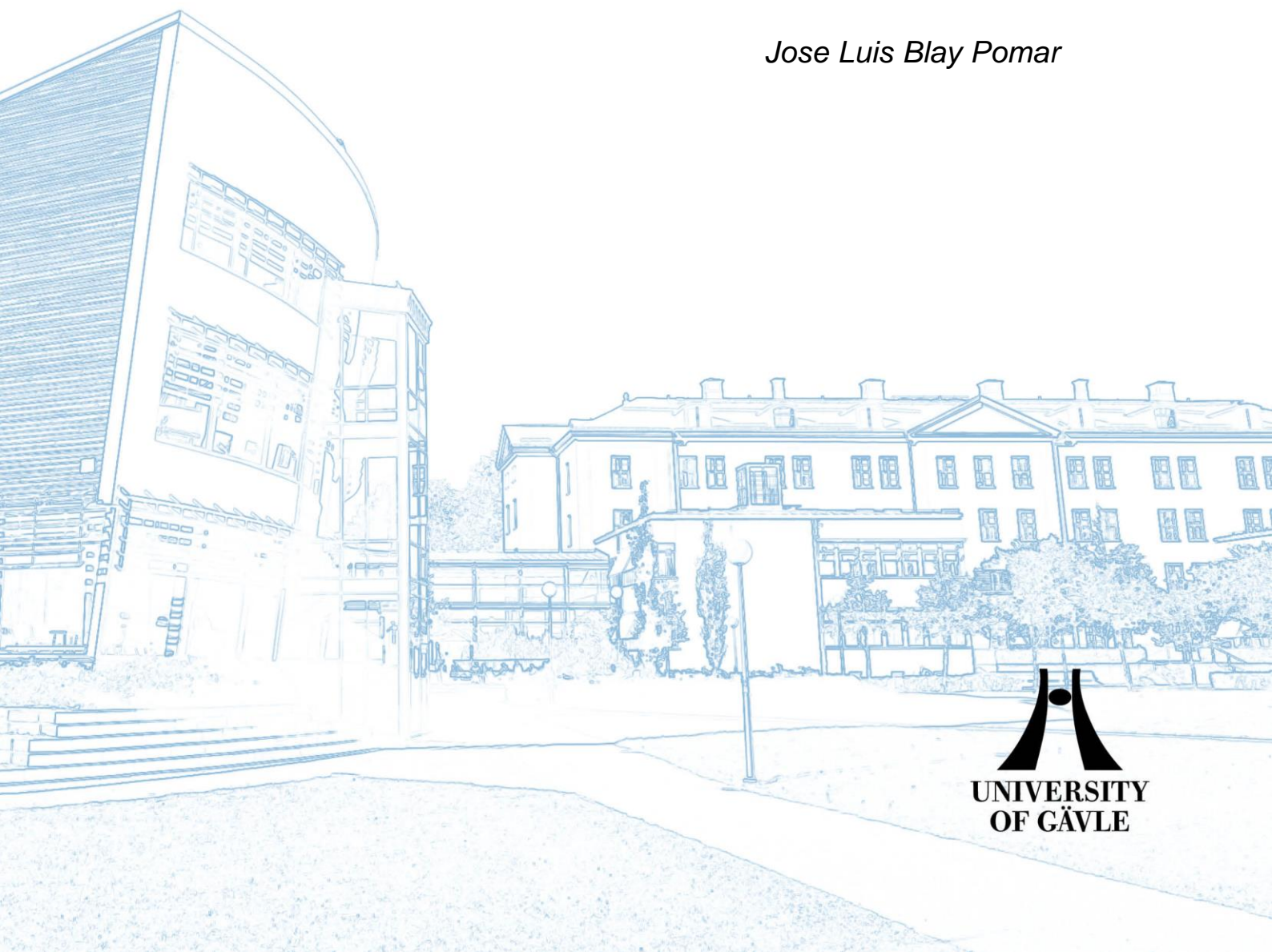


Assessment of offshore wind transmission technologies for green hydrogen production

Case study in Gävleborg County, Sweden

Jose Luis Blay Pomar



This work is published via open access and is licensed with a
Creative Commons Attribution-NonCommercial 4.0
International (CC BY-NC 4.0) license.

Research Report No. 11
urn:nbn:se:hig:diva-41595

Distribution:
Gävle University Press
SE-801 76 Gävle, Sweden
gup@hig.se

Assessment of offshore wind transmission technologies for green hydrogen production

Case study in Gävleborg County, Sweden

Jose Luis Blay Pomar

Faculty of Engineering and Sustainable Development
Department of Building Engineering, Energy Systems and Sustainability Science



Abstract

The usage of green hydrogen is expected to reduce the annual greenhouse gas emissions by 2% that are currently generated by the consumption of fossil-based hydrogen, while also hard-to-abate industries that are difficult to shift to low-carbon alternatives in the future. Gävleborg county, a crucial part of Sweden's industrial value chain, aims to decrease its carbon footprint in hydrogen-based industries by producing competitive green hydrogen by deploying offshore wind energy along the Gävleborg coast. To enhance the industrial competitiveness of Gävleborg by making the most of the wind resources in the area, it is important to select suitable energy transmission technologies. Therefore, this study aims to evaluate the potential of different offshore wind-to-shore technologies and assess the feasibility of hydrogen production for dedicated future offshore wind plants in the region.

This case study examined the annual average power and energy recovery from wind resources in two different locations along the Gävleborg coast. More than 100 000 wind data values collected over 14 years from the New European Wind Atlas database were analyzed using the continuous Weibull function. Moreover, to evaluate the energy losses in the transmission to shore it was used the π -equivalent schema for either high voltage alternating current (HVAC) or high voltage direct current (HVDC), considering different voltage levels or the usage of reactive compensation. Finally, the power and energy input requirements of the largest operational PEM electrolyzer for hydrogen production were assessed.

Three different offshore wind farm designs have been proposed for analysis, varying the installed power capacity and distance from the shore in accordance with the current offshore wind farm prospects in the region. On the one hand, designs with lower power capacity and closer to the shore are more likely to use HVAC technology with low voltage levels and little significance on reactive compensation. On the other hand, larger offshore wind designs will potentially use either HVAC technology with higher voltage levels and reactive compensation, or HVDC technology. After analysis, it can be concluded that the deployment of any of the suggested offshore wind designs will have a significant impact on the region's energy mix, covering most of the current Swedish hydrogen demand when considering dedicated offshore wind-to-hydrogen plants. Nevertheless, most of these plans are currently in the initial stages of conception and planning and are awaiting political initiatives and technological advancements to reach a level of economic competitiveness.

This study also shows that Gävleborg county has a significant opportunity to become a prominent hydrogen producer in the next few decades; not only reducing the national carbon footprint, but also providing a significant business opportunity for the region. Furthermore, the selection of the best-suited offshore wind-to-shore technology will have a great impact in the investment and efficiency of the project, thus highlighting the most cost-effective and competitive offshore wind farms in the region.

Keywords: Gävleborg county, offshore wind, energy transmission, designs, distance to shore, reactive compensation, π -equivalent schema

Sammanfattning

Användningen av grön vätgas förväntas minska de årliga utsläppen av växthusgaser med 2 %, för närvarande genererade av förbrukningen av fossilbaserad vätgas, samt från industrier som har svårt att övergå till alternativ med låga koldioxidutsläpp i framtiden. Gävleborgs län, som är en viktig del av Sveriges industriella värdekedja, har som mål att minska sitt koldioxidavtryck inom vätgasbaserade industrier genom att producera konkurrenskraftig grön vätgas med hjälp av havsbaserad vindkraft längs Gävleborgs kust. För att öka Gävleborgs industriella konkurrenskraft genom att utnyttja vindresurserna i området på bästa sätt är det viktigt att välja lämplig teknik för energiöverföring. Den här studien syftar därför till att utvärdera potentialen hos olika tekniker för överföring av havsbaserad vindkraft till land och bedöma genomförbarheten av vätgasproduktion för dedikerade framtida havsbaserade vindkraftverk i regionen.

I denna fallstudie undersöktes den årliga genomsnittliga effekten och energitillförseln från vindresurser på två olika platser längs Gävleborgs kust. Mer än 100 000 vinddatavärden som samlats in under 14 år från databasen New European Wind Atlas analyserades med hjälp av den kontinuerliga Weibull-funktionen. För att utvärdera energiförlusterna i överföringen till land användes dessutom π -ekvivalentschemat för antingen högespänd växelström (HVAC) eller högespänd likström (HVDC), med beaktande av olika spänningsnivåer eller användning av reaktiv kompensation. Slutligen bedömdes effekt- och energibehovet för den största operativa PEM-elektrolysören för vätgasproduktion.

Tre olika layouter för havsbaserade vindkraftparker har föreslagits för analys, där den installerade effektkapaciteten och avståndet från kusten varierade i enlighet med de aktuella utsikterna för havsbaserade vindkraftparker i regionen. Å ena sidan är det troligare att layouter med lägre effektkapacitet och närmare kusten använder HVAC-teknik med låga spänningsnivåer och liten betydelse för reaktiv kompensation. Å andra sidan kommer större havsbaserade vindkraftsanläggningar potentiellt att använda antingen HVAC-teknik med högre spänningsnivåer och reaktiv kompensation eller HVDC-teknik. Efter analysen kan man dra slutsatsen att utbyggnaden av någon av de föreslagna havsbaserade vindkraftsutformningarna kommer att ha en betydande inverkan på regionens energimix och täcka större delen av Sveriges nuvarande vätgasbehov om man beaktar dedikerade havsbaserade vindkraftverk för vätgasproduktion. De flesta av dessa planer befinner sig dock för närvarande i ett inledande skede av utformning och planering och väntar på politiska initiativ och tekniska framsteg för att nå en nivå av ekonomisk konkurrenskraft.

Denna studie visar också att Gävleborgs län har en betydande möjlighet att bli en framstående vätgasproducent under de närmaste decennierna, vilket inte bara minskar det nationella koldioxidavtrycket utan också ger regionen en betydande affärsmöjlighet. Vidare kommer valet av den bäst lämpade tekniken för överföring av havsbaserad vindkraft till land att ha stor betydelse för investeringar och effektivitet i projektet, och därmed bidra till de mest kostnadseffektiva och konkurrenskraftiga havsbaserade vindkraftparkerna i regionen.

Keywords: Gävleborg county, offshore wind, energy transmission, designs, distance to shore, reactive compensation, π -equivalent schema.

Acknowledgments

The work with this report was carried out within the project Systemanalys av vätgaslösningar (System Analysis of Hydrogen Solutions), funded by the European Regional Development Fund of the European Union, Region Gävleborg, the University of Gävle, Gävle Energi and Svea Vind Offshore.

I would like to express my sincere gratitude to those who allowed me to participate in the hydrogen research group at Högskolan i Gävle, especially Karl Hillman. Thanks for trusting in my ambition and appreciating my sincere motivation to learn from every experience and give my best to help this group of highly qualified individuals both personally and professionally.

Thanks to my supervisor Peder Zandén Kjellén, not only for leading me to my dreamed first work experience to fight climate change and improve my professional skills with inspiring work ethics and methodologies; but also, for his personal treatment, giving me motivation and wish suggestions when I needed them the most. I am sure that these enriching moments will remain with me over time.

Lastly, I would like to thank my family for encouraging me to follow my dreams, their love is my fuel to keep going.

Abbreviations

Greenhouse gas	GHG
High voltage alternating current	HVAC
High voltage direct current	HVDC
Alternating current	AC
Direct current	DC
European Union	EU
Alkaline	ALK
Proton exchange membrane	PEM
Electrolyzer	EL
New European Wind Atlas	NEWA
Probability density function	dp
Shape factor	k
Scale factor	c
Coefficient curve	Cp
Cut-in velocity	Va
Nominal velocity	Vn
Cut-down velocity	Vp
Annual average recovered power	\bar{P}_d
Annual average recovered energy	Ed
Resistance	R
Inductive reactance	XL
Impedance	Z
Admittance	Y

Table of Contents

1. Introduction	1
2. Technology overview	3
2.1 Offshore wind turbines	3
2.1.1 Bottom-fixed turbines	3
2.1.2 Floating turbines	3
2.2 Energy transmission technologies	4
2.2.1 High voltage alternating current	4
2.2.2 High voltage direct current	5
2.2.3 Hydrogen pipeline	5
2.3 Electrolyzer technologies	5
2.3.1 Alkaline water electrolyzer	6
2.3.2 Proton exchange membrane electrolyzer	6
3. Methods	7
3.1 Wind resource study	7
3.2 Hydrogen production	8
3.3 Energy transmission losses	9
3.4 GHG emissions assessment	10
4. Case study description	11
5. Results	14
5.1 Wind resource potential	14
5.2 Hydrogen production	14
5.3 Energy transmission losses	16
5.4 GHG emission assessment	17
6. Discussion	18
7. Conclusion	20
8. References	22
Appendix A	27
Appendix B	28

1. Introduction

After decades of data collection and analysis of complex climate models, the science on the human contribution to modern global warming is quite clear: human emissions of GHGs (greenhouse gases) and fossil fuel-based activities are the main cause of the ongoing unprecedented global warming observed since 1950 [1]. The UN (United Nations) General Assembly, made up of nearly 200 nations from around the world, has decided that its members must work together to achieve sustainable development that meets the needs of the present without compromising the ability of future generations to meet their own needs, as set out in the 17 goals of the 2030 Agenda [2]. Specifically, the Paris Agreement signed in 2016, highlights the global interest in focusing efforts on drastically reducing GHG emissions, with the clear objective of keeping the average global temperature increase below 2°C compared to pre-industrial levels, and continuing efforts to limit the increase to 1.5°C, recognizing that this would significantly reduce the risks and effects of climate change [3].

More than 2% (830 million tons) of global GHG emissions annually come from hydrogen current consumption, as more than 98 percent of the current hydrogen production is from either reformed natural gas (75%) or gasified coal (23%). This leads industrial processes such as oil refining and the production of ammonia, methanol or steel with a high environmental impact [4]. For the upcoming years, hydrogen requirements are expected to grow exponentially due to its potential role in the decarbonization of hard-to-abate sectors, such as heavy industry, shipping, aviation, and heavy-duty transport, where alternative solutions are either unavailable or difficult to implement [4]. In this regard, the importance of developing a future carbon-neutral hydrogen economy has been globally accepted, as reflected in the growing number of governments adopting hydrogen technology deployment strategies and targets [4]. The last 2021, more than 750 initiatives were announced in a European project pipeline [5], [6], in which potential hydrogen users have proposed plans throughout the value chain within the three parts of an energy system: production, distribution, and end use; ensuring an efficient and reliable energy supply minimizing energy losses [7].

Low environmental impact through hydrogen production is at the heart of the hydrogen economy, where an extensive range of alternative hydrogen production processes must find their niches in the market, such as the use of nuclear energy subproducts, biomass processes, or applying carbon capture and storage technology in existing fossil fuel-based plants [8]. But the principal technology expected to produce the bulk of renewable (green) hydrogen globally is electrolysis, which current installed capacity has reached 0.5 GW, but only with the projects in the pipeline could lead to an electrolyzer capacity of up to 200 GW by 2030 [9], [10].

Sweden will face a drastic transformation of its industrial and energy sectors to meet the national target of zero emissions by 2045, where the offshore wind has the potential to deploy 41 GW of economic-viable projects, becoming a key driver towards decarbonization. This transformational challenge for the power sector comes with electricity demand growth of between 123% and 193% by 2050, with emissions reductions, industry growth, and hydrogen production being essential factors. For instance, producing the current fossil-based Swedish hydrogen demand of over 150 000 metrics with green electrolysis will potentially reduce national emissions by 14 percent and increase the electricity demand by over 50 TWh, which must be met by large deployments of large renewable energy production plants [11], [12].

Historically, Sweden has been a net exporter of electricity to neighboring countries and in 2022 has become the largest exporter in Europe [13], using power transmission technologies such as high voltage alternating current (HVAC) or high voltage direct current (HVDC). Future scenarios with a large deployment of renewable energy plants, especially a considerable injection of offshore wind power, can launch Sweden to be a driver of green hydrogen in Europe with prices below USD 3 per kilogram, less than half of some nearby countries such as Germany or Denmark [14]. A critical factor in offshore wind energy production is the power transmission technology used to bring the

¹ Magnitude order of the proposed wind farm power capacity.

² Preliminary approximate distance to Swedish mainland, willing to change with consultations and trials.

captured energy to shore, as it reflects a significant part in the investment and energy losses through plant operation, and thus a direct impact on the levelized cost of energy, and thus levelized cost of hydrogen [15]. Since the deployment of the first offshore wind farms, the most widely used transmission technology has been HVAC, due to its state of maturity and the proximity of the projects to the coast. However, HVDC has become more relevant as the offshore wind sector expands into larger projects, further offshore, in search of larger wind resources and installed capacities exceeding GW of power. Though, alternatives such as offshore hydrogen production are popping up to address energy losses during energy transport to shore, where hydrogen must be pumped through pipelines to shore [16].

The Gävleborg coast has been selected by many companies as a strategic location for the first deployment of large-scale offshore wind energy in Sweden, due to its favorable seabed characteristics, high wind resource potential, and offshore demarcation [17]. This report aims to assess the prospects of diverse offshore wind-to-hydrogen technologies along Gävleborg's coast by analyzing current offshore wind plans in the region and evaluating the potential of three proposed wind farm designs with regard to capacity power and distance to shore. To assist this purpose, the following research questions are addressed:

- Which energy transmission technology—HVAC or HVDC— is best suited to deliver the most energy to shore for each offshore wind farm layout?
- How does the hydrogen production vary for each design depending on the applied energy transmission?
- Which is the GHG emission impact of offshore wind-to-hydrogen compared with other typical hydrogen production processes?

To achieve this objective, relevant literature and data sources were analyzed and synthesized to provide an updated view of the current state of the offshore wind-to-hydrogen industry, with a special focus on the current most promising technology most likely to be applied in the region.

This report targets stakeholders who are interested in the potential business opportunities that arise from bulk green hydrogen production from offshore wind farms in the Gävleborg county region and also, policymakers who are involved in planning future offshore wind deployment requirements in the region. Even more, this study might be relevant for companies that are taking the initial steps toward energy transmission selection studies in similar projects. Additionally, the report can serve as inspiration for future in-depth studies related to the offshore wind-to-hydrogen industry on the Gävleborg coast.

The project is a result of two three-month contracts, the first half-time job and then full-time enrollment at the Högskolan i Gävle. Due to the project's given timeframes and changes in plans over time, some assumptions were made in this study to answer the research questions presented. These assumptions were primarily related to the electrical calculations used in the study.

It is beyond the scope of this study economical aspects, in-depth footprint reduction analyses or the precise selection of the wind turbine type regarding security or productivity parameters. Furthermore, by using the wind resource study outputs future follow-up research studies might dimension the energy storage onshore or the power capacity of the electrolyzer for each layout.

¹ Magnitude order of the proposed wind farm power capacity.

² Preliminary approximate distance to Swedish mainland, willing to change with consultations and trials.

2. Technology overview

The energy transition, motivated by climate change evidence and stimulated by political and private actors, comes with structural changes in the overall energy system from supply to consumption [18]. Throughout this process, several technical alternatives must be tested and analyzed in conjunction. The ultimate objective is to approach the problem from different perspectives, addressing the three main dimensions of sustainable development: social, economic, and ecological sustainability [19].

This chapter highlights the main components involved in offshore wind to hydrogen projects and provides an overview of their current status and future prospects. To achieve this objective, relevant literature and data sources were analyzed and synthesized to provide an updated view of the current state of the offshore wind-to-hydrogen industry.

2.1 Offshore wind turbines

Most human beings around the globe are located near the shore, covering only 10% of the planet's land surface[20]. This natural behavior of humankind is a direct advantage for reducing energy losses in the energy system by producing electricity close to demand with offshore wind farms, which is expected to produce more than 30% of the global future energy consumption, with a 13 percent annual growth in power installed from 2020 to 2050 [21].

European offshore wind capacity accounts for 28 GW in 2021 and is set to increase to over 116 GW by the end of this decade, with a special focus on the EU main sea basins [21]. In the north of the continent, eight European Union countries bordering the Baltic Sea agreed to increase the offshore wind power generation capacity to 20 GW by 2030, highlighting Sweden's most ambitious plans with over 8,5 GW in the pipeline[22]. The combination of several offshore wind turbine technologies will enhance the installed capacity, enabling the projects to adapt to factors such as wind resources potential, seabed depth, restricted delineated areas, or environmental and visual impact.

Regarding turbine anchoring there are two main available technologies, in this subsection are presented their respective characteristics, current stage, and future global prospects.

2.1.1 *Bottom-fixed turbines*

The majority installed and the totality of the commercially operative wind turbines are bottom-fixed based, with powers over 10 MW for new-generation units [23]. Europe was the first region to make a major deployment of this technology, with 28 GW installed today and possessing most of the related technology, although China is expected to take the lead in both aspects in the coming decades [24]. European shallow waters up to 60 meters in depth are ideal for the rollout of bottom fixed foundations and introduce a clean and cheap source of energy into the power grid. However, some directly related drawbacks are the environmental and visual impact, as shallow waters are most likely to be located close to the coast, or the high investment costs and complexity of offshore anchoring[25].

2.1.2 *Floating turbines*

EU has set out the objective to reach 300 GW offshore wind capacity by 2050 and the Baltic Sea can realize almost one-third of this capacity by combining both bottom-fixed and floating turbines, which potentially opens the possibility to exploit the highest wind potential resources further from the coast [26]. Floating foundations are expected to play a key role in the offshore wind industry in the next decades, as they have added benefits such as the ability to be towed out to the energy production site, allowing them to be assembled in port and then be located in high wind potential locations regardless the large seabed depths [25]. So far, floating tech is still in the development stage and higher investment is required; an installed capacity of 8 GW out of 116 GW offshore wind by 2030 is foreseen in the EU [21].

¹ Magnitude order of the proposed wind farm power capacity.

² Preliminary approximate distance to Swedish mainland, willing to change with consultations and trials.

2.2 Energy transmission technologies

The global acceptance of reducing fossil fuel consumption, expressed in several key agreements in recent years, has postulated renewable energies as the future key driver for achieving the environmental goals of modern society and electricity is expected to become the central energy carrier by 2050, growing from a 20% share of final consumption to an almost 50% share [27]. Intrinsically, this energy transition is accompanied by a massive evolution of power transmission technologies that seek to postulate their advantages to adapt to more renewable power plants with high technical and economic efficiency solutions.

Energy losses through transportation are a key relevant aspect when assessing the potential of deploying an offshore wind farm, as final energy production and investment costs are directly related. In this subsection, we will discuss the various energy losses associated with different types of electrical current (alternating or direct current) and energy carriers. Specifically, we will consider the current offshore wind industry in light of each technology, perspective, and limitations

2.2.1 High voltage alternating current

High voltage alternating current (HVAC) is the most common method for electrical power distribution in large-scale energy projects, such as offshore wind farms located over long distances. The HVAC voltage level range from 36-66kV, typical output values in offshore wind farms using set-up transformers placed inside the turbine nacelle, to over 400kV using large-scale transformers [28]. HVAC reduces energy losses due to cable resistance by decreasing the ampacity of transmission lines, resulting in more efficient and cost-effective solutions [29]. However, the transmission capacity of the submarine cable is limited by the capacitive resistance across the line, several reactive compensation technologies are used to reduce this drawback by improving the final power reaching the coast, such as [30]:

- Cable compensation: The installation of inductors, such as shunt reactors along the lines, provides additional reactive power support to the system, helping to reduce losses and improve the overall efficiency of the power transmission system.
- Power electronic or active cable: These systems use advanced power electronics to control and compensate the reactive power flow in the cable, improving grid stability and quality, and optimizing the reactive power compensation schemes, avoiding the bottleneck point of cable ampacity.

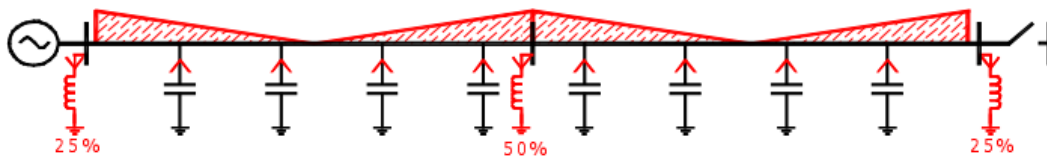


Figure 1 Loading scheme distribution example of an open-end cable line due to the capacitive charging current of reactive power compensation [31].

The choice of technology will depend on the offshore wind farm project's specific needs and constraints, including the cable's length, voltage level, and power quality requirements. However, cable compensation and power electronic interfaces are currently the most widely used technologies for compensating reactive energy losses in offshore cables [30]. The main energy losses are represented by the cable transmission resistance (effective resistance, inductance, and capacitance) and the transformers (copper and iron losses, plus leakage inductance and stray losses).

From an economic perspective, it's important to consider that cables designed for higher voltage capacity may necessitate the use of more sophisticated materials and manufacturing techniques, leading to an associated increase in cost [32].

¹ Magnitude order of the proposed wind farm power capacity.

² Preliminary approximate distance to Swedish mainland, willing to change with consultations and trials.

2.2.2 High voltage direct current

The first steps of high voltage direct current (HVDC) for long-distance applications were taken with the connection of mainland Sweden to Gotland in 1950, this technology is predicted to expand as the need for renewable energy sources grows, and advancements in power electronics will enhance efficiency and lower the cost of HVDC systems [33]. This setup involves using converters and inverters to switch from the alternating current generated by the wind turbine into DC, and then back into AC before injecting it into the electricity grid.

HVDC technology is favored in remote applications due to its ability to transmit electricity with minimal losses offsetting the high investment prices related to the power electronics required for this setup, which is particularly important for the remote locations of many offshore wind farms,. Some large offshore wind farms currently using this technology are Dogger Bank Wind Farm, Hornsea Project One, and Kriegers Flak with 3.6 GW, 1.2 GW and 600 MW, respectively [34]–[36].

The most promising variant of HVDC expected to play a significant role in the future of electrical power transmission is the voltage-sourced converter, which uses a multi-level converter instead of two-level converters which provides improved performance and greater control over the transmitted power. The main energy losses are represented by the cable transmission resistance (effective resistance) and the conjunction of the inverter plus converter [37].

2.2.3 Hydrogen pipeline

The abundance, energy density, and versatility of fossil fuels make the urgent energy transition a challenging task that requires investment in research and development of cutting-edge technologies, as well as in the construction of new infrastructure for renewable energy generation, storage, and distribution[38]. Certainly, maximizing the potential of renewable energy resources is pivotal in meeting environmental goals without sacrificing economic growth and social stability, on top of that, some of the most optimal wind resources are located far from the coast and the way to transmit the captured energy to shore is a relevant technical aspect that must be closely studied to reach the most cost-effective and efficient solution [39].

The hydrogen industry has seen a rise in popularity in recent years, with an increasing interest in hydrogen-based energy transmission solutions. Hydrogen pipelines have emerged as a promising option, offering low energy losses during transmission, making them ideal for remote offshore wind locations. There are several planned projects in the EU, such as the Baltic Sea Hydrogen Collector or H2Med, which aim to transport hydrogen as an energy carrier through hundred kilometers distances; these developments point towards a promising future for the hydrogen industry and its potential impact on the energy sector[40], [41]. Towards 2050, there will be a considerable growth of off-grid wind capacity dedicated to green hydrogen production through electrolysis, currently, projects such as Wind2Hydrogen or Hywind Tampen [42], [43] are planned to be deployed in the following years to make the first steps to analyze these solution's technical and economic viability [24].

However, state-of-the-art hydrogen pipeline alternative needs a higher investment than the electrical-based options and with the current technology outlook and according to the related literature, it will be cost-effective for sites located more than 200 km offshore [44], [45].

2.3 Electrolyzer technologies

Electrolysis is a process of applying electricity to water, splitting the water molecules to produce hydrogen and oxygen gas, and heat. The electrolyzer market is experiencing rapid growth, with over 460 electrolyzer projects under development that could lead to an installed capacity of around 200 GW around 2030, driven by significant investments and technological advancements to reduce the cost of green hydrogen production [46]. Efforts from both the private and public sectors are focused on achieving economies of scale and lowering procurement costs for materials, leading to major hydrogen supply projects with capacities reaching hundreds of megawatts in the near future. Improved design and construction, combined with declining electricity and electrolyzer prices, hold the potential to decrease the cost of green hydrogen by up to 80% [47].

¹ Magnitude order of the proposed wind farm power capacity.

² Preliminary approximate distance to Swedish mainland, willing to change with consultations and trials.

The field of electrolyzer technology encompasses a range of options based on several key factors, including the type of electrolyte utilized, the design of the cell stack, and the materials used in construction. As numerous hydrogen supply projects are being developed, companies must select the most advantageous option in terms of increasing project profitability. Some key factors to be considered when evaluating electrolyzer technologies include long-term operational stability, plant lifespan, cost-to-power ratio, and pressurized delivery capability. To ensure optimal results, a systematic and thorough evaluation of the available options must be conducted, considering the specific requirements of the intended application [48].

The two predominant options that have been considered in large-scale hydrogen production schemes, due to their demonstrated maturity, are presented in this section:

2.3.1 Alkaline water electrolyzer

The ALK (Alkaline) electrolyzer is an economical and mature technology that offers a long plant lifetime and a low cost-energy ratio thanks to the non-precious metals used in its production. This modular and stackable technology, currently reaching 4 MW per unit, is widely used in chlorine production, with more than 700 MW installed worldwide. [49],[50]. Due to the materials and the nature of the electrolyte ALK electrolyzer works in constant current and has a difficult splitting of water molecules, two problems that must be overcome to adapt to the future large hydrogen industry that will need pure hydrogen production and work within variable loads based on renewable energies. Its lower price than alternatives and current advances focused on evaluating grid intermittency and load control make this technology more attractive for large hydrogen production plants in the future. [48].

The main objective is to increase the operating time by using intelligent system designs and effective operational techniques. Initially, using conventional energy storage devices to stabilize dynamics is a proper option. However, it's better to let alkaline water electrolyzers handle dynamics directly to reduce costs and increase efficiency [48]. The choice of this technology must be studied carefully, and factors such as hydrogen purity and input load are important. It's expected that the installed power of this capacity will double worldwide in 2023 [49].

2.3.2 Proton exchange membrane electrolyzer

The PEM (proton exchange membrane) works through a solid polymeric membrane, with water supplied at the anode. The membrane splits the water into hydrogen ions (H^+) and oxygen, with only the hydrogen ions passing through the membrane to create high-purity hydrogen at the cathode. PEM electrolyzer technology, typically manufactured with an acidic membrane and noble materials, is not dependent on stable operating conditions, allowing the system to vary its performance quickly and efficiently following energy supply fluctuations of renewable energy-based power plants. The composition of the electrolyzers results in more compact and costly stacks, with safe and stable competitive operation between 50 000 and 80 000 hours [51].

High expectations in the hydrogen industry have accelerated investment and innovation in PEM technology, resulting in significant cost reductions through mass production, technological improvements in materials science, manufacturing processes, and system design. PEM electrolysis technology is already commercially available and is projected to grow its power capacity by 4 times by 2023 and is a leading candidate for producing most of the future's off-grid energy production, which by 2030 will be 110 GW worldwide [21].

¹ Magnitude order of the proposed wind farm power capacity.

² Preliminary approximate distance to Swedish mainland, willing to change with consultations and trials.

3. Methods

The examination of the offshore wind initiatives in Gävleborg county serves as a fundamental precursor to guide the investigation with the best favorable approach. Therefore, this report will present several specific alternatives in the area as case studies, focusing efforts on defined designs. The literature parameters and methodologies used in the wind resource assessment, energy losses through transmission, and hydrogen production are sourced from peer-reviewed papers or research reports. In order to achieve a more accurate approximation of the report's goal, certain suppositions have been made. The following chapter explains the principal methodologies applied to respond to the above presented research questions.

3.1 Wind resource study

The New European Wind Atlas (NEWA) is an important resource for engineering professionals involved in site assessment for wind energy projects. NEWA serves as a standard tool for manufacturers, developers, public authorities, and decision-makers to reduce uncertainties in determining wind conditions. This freely accessible public website provides high-resolution and long-term datasets of wind resources across Europe [52]. This report studies the potential wind located in Point A and Point B at Table 1, analyzing more than 100 000 hourly wind data collected over 14 years estimated at 100 meters in height. The procedure is divided into the wind data treatment, the turbine characterization, and ultimately the combination of both studies to assess the energy production.

Table 1 Points A and B coordinates

Point A	Point B
60°57' N 17°34' E	60°58' N 18°13' E

Firstly, to analyze wind resources, we utilized the probability density function (dp,exp), which arranges wind speed data in ascending order and provides the probability of a wind value falling within a specific range of speeds. To simplify data management, we then estimated Weibull's continuous distribution ($dp,Weibull$), which is widely used in the wind energy sector (Equation 1). This distribution excludes calm wind data and is governed by two key variables: the shape factor (k) and the scale factor (c). The shape factor represents wind speed variation over time and determines the symmetry of the function, while the scale factor is linked to the average speed, thus a higher scale factor corresponds to a higher average speed.

Equation 1 Weibull's distribution

$$d_{p,Weibull}(V) = \frac{K}{c} \left(\frac{V}{c}\right)^{K-1} \exp \left[-\left(\frac{V}{c}\right)^K \right]$$

To obtain the Weibull parameters that best adapt to the wind resources, one common practice in the wind industry to achieve an accurate approximation of the Weibull function and maximize energy extraction is to minimize the difference between experimental and continuous probability values considering the great influence of the wind velocity in the final energy production, as proceeded in [53].

In order to make the most of the wind power in a specific area, it's important to fully grasp the characteristics of the chosen wind turbine. These include the cut-in and cut-out wind speeds, rated power, swept area, and the power coefficient curve ($C_p(V)$), which represents the efficiency of the turbine at different wind speeds, and it's calculated as [53]. With the offshore wind industry growing at a rapid pace, the use of larger turbine sizes provides the most cost-effective and efficient solutions to harness the maximum potential of a given wind site. The table in Appendix A presents the key characteristics of the turbine selected for this project, which is currently undergoing extensive testing and verification to ensure its performance meets the desired specifications.

¹ Magnitude order of the proposed wind farm power capacity.

² Preliminary approximate distance to Swedish mainland, willing to change with consultations and trials.

Finally, after defining the wind data treatment and the turbine characterization and including the calm wind data to Weibull's function, the results of annual average recovered power per swept area square meter ($\overline{P_d}$) and average energy recovered per swept area square meter (E_d) can be obtained from Equation 2 and Equation 3, respectively. These equations are governed by the V_a , cut-in velocity at which the wind turbine starts to generate electricity, V_n , nominal velocity at which the wind turbine starts generating the maximum power, and V_p , cut-down velocity at which the aerogenerator stop producing electricity for safety reasons regarding high wind velocities.

Equation 2 Wind power recovered

$$\overline{P_d} = \int_{V_a}^{V_p} P_r(V) d_p dV = \int_{V_a}^{V_n} \frac{1}{2} \rho C_p(V) V^3 d_{p,Weibull} dV + \int_{V_n}^{V_p} P_n d_{p,Weibull} dV$$

Equation 3 Annually energy power recovered

$$E_d = 8760 \overline{P_d}$$

3.2 Hydrogen production

The suitable characteristics presented in the technology overview chapter, make PEMEL the most attractive technology for pure hydrogen generation at scale coupled with renewable energy production and its modularity that allows a simple scaling. Furthermore, through the literature, there is a clear tendency of results supporting PEMEL as the best option for large green hydrogen production.

When considering the performance of an electrical system like a PEMEL, technical features such as hydrogen pressure output, water consumption, and molecule purity are important. However, the primary selection parameter for these systems is hydrogen production, which can be broken down into power and energy parameters. The power parameter refers to the rate at which the electrolyzer can produce hydrogen, typically measured in watts. The energy parameter, on the other hand, refers to the total amount of hydrogen that can be produced by the electrolyzer over time, typically measured in watt-hours or kilowatt-hours. Selecting an appropriate PEM electrolyzer for a renewable energy application requires considering both the power and energy parameters to ensure that the system can efficiently and reliably convert electrical energy to hydrogen.

When determining the power requirements for producing hydrogen, a linear approximation is often used, as described in a peer-reviewed article published in "Applied Science" by Gonalo Calado and Rui Castro in 2021. The Cummins HyLYZER series, which currently holds the title for the world's largest PEM electrolyzer with a power rating of 20 MW, was used as a basis for this approximation as represented in Table 2 [53].

Table 2 Electrolyzer power-hydrogen performance.

Power (MW)	Hydrogen mass (kg/day)
1	431
5	2 157
25	10 775
50	21 571
75	32 356
100	43 142

The energy input requirements per kilogram of hydrogen are determined by the electrolyzer's electrical efficiency, which can be represented as a percentage or an energy indicator. Currently, the energy requirements to produce a kilogram of hydrogen range from 80 kWh/h2 kg to 50 kWh/h2 kg, depending on the technology used. The International Renewable Energy Agency (IRENA) has set targets for key performance indicators of PEM electrolyzers, aiming for less than 45 kWh/h2 kg with the latest innovations. For this research, the electrical efficiency of the largest PEM

¹ Magnitude order of the proposed wind farm power capacity.

² Preliminary approximate distance to Swedish mainland, willing to change with consultations and trials.

electrolyzer, the Cummins HyLYZER 4000-30, was selected as the basis for calculations, as represented in Figure 2 [53].



Figure 2 Case study electrolyzer electricity efficiency.

3.3 Energy transmission losses

Based on the literature and technology review, can be concluded that electrical alternatives are the most cost-effective option for the designs presented on the Gävleborg coast due to their relatively short distance-to-shore. To reach the report's objective the energy transmission losses must be assessed and compared by studying the main components required to transport energy to shore using either HVAC or HVDC; thus, similar losses regardless the configuration such as interrail and grid connections have no further interest in this study. In this section, it has been carefully selected values from peer-reviewed articles and suppliers' datasheets through an intensive analysis.

In offshore wind farms, cable losses account for a significant percentage of the overall energy transportation losses [54]. The most relevant energy losses are attributed to inductive resistance caused by the fluctuation of the magnetic field generated by alternating current, and heat losses due to resistive resistance, where the electricity voltage through the transportation plays a key role. Among the documents published by the companies stating interest in the future deployment of offshore wind farms along Gävleborg coast, there is a large variety of voltage considerations from 36kV to 320 kV.

The examination of energy losses in HVAC systems has primarily concentrated on evaluating cable losses using the π -equivalent schema. This method simplifies the evaluation of a real spatially distributed system by generating a discrete topology that approximates the behavior of the distributed elements [55], [56]. These components, represented in Figure 3, are resistance R , inductive reactance X_L , impedance Z and admittance Y , the selected values can be reviewed in Appendix B.

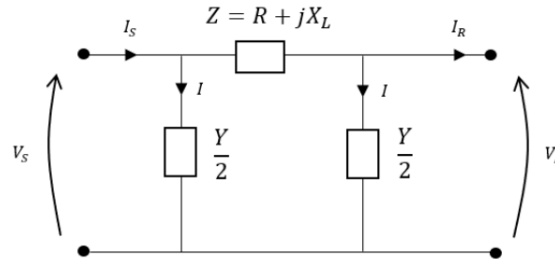


Figure 3 π -equivalent schema

On the one hand, V_s value represents the transmission voltage, either directly from the wind turbine or after transformer, with the assumption of non-reactive power at this point as the wind turbine doubly-fed induction generator, can vary the reactive output depending on the fed electricity in the rotor[57]. On the other hand, the V_r value is the voltage arriving at the shore, typically lower than the V_s due to the voltage losses through the different resistances in the way. In this study, reactive power compensation has been supposed so that the system injects zero reactive power to the connection point. Furthermore, transformer losses have been set as 0.6% power drop every 400 MW offshore wind farm power, a value in line with different dedicated studies as [57], [58]

The analysis performed in relation to HVDC cables has a relatively lower complexity since there is no reactive generation through transport. The most relevant factor, apart from the proper investigation of HVDC cable data sheets with resistance values per km (Appendix B), has been the evaluation of losses in the power electronics, both in the offshore converter and in the onshore inverter.

¹ Magnitude order of the proposed wind farm power capacity.

² Preliminary approximate distance to Swedish mainland, willing to change with consultations and trials.

After conveying large research in the literature has been set a 1% power drop for every 1200 MW offshore wind farm power, a value in line with different dedicated studies [54], [57], [59]

3.4 GHG emissions assessment

Offshore wind-to-hydrogen deployment offers significant environmental benefits, making it a crucial part of the renewable revolution. This research report aims to estimate the reduction in greenhouse gas (GHG) emissions by comparing the environmental impact of producing hydrogen through typical fossil-based processes and electrolysis in Sweden.

This report studies the potential environmental impact from the total integration of each design for dedicated hydrogen production by using CO₂ emission ratios per kilogram of hydrogen. On the one hand, electricity values represented in Table 3 has been extracted from [51] and adapted to the study units applying the electricity to hydrogen ratio at E. On the other hand, the grey hydrogen emissions represented in Table 3 has been extracted from [60] considering steam methane reforming as the main current hydrogen production processes.

Table 3 GHG emissions assumptions for hydrogen production

Electricity emissions from Swedish Energy mix (kgCO ₂ /kgH ₂)	Electricity emissions from offshore wind production (kgCO ₂ /kgH ₂)	Grey Hydrogen emissions from steam methane reform- ing (kgCO ₂ /kgH ₂)
2.4	0.6	12.13

In this report, the emissions for processes using electrolysis dismiss the electrolyzer lifecycle environmental impact due to its minimum impact compared with the electricity part [61]. Furthermore, the ratios are susceptible to change overtime as both the Swedish grid mix and the offshore wind energy evolve.

¹ Magnitude order of the proposed wind farm power capacity.

² Preliminary approximate distance to Swedish mainland, willing to change with consultations and trials.

4. Case study description

The purpose of this chapter is to provide a comprehensive overview of the regional landscape surrounding offshore wind and hydrogen production. Specifically, it will explore the potential of Gävleborg county for coupling these two technologies, highlighting the various projects in this area and proposing designs to guide the study.

Gävleborg and its surrounding counties form a robust industrial network cluster dominated by the steel industry, which currently relies heavily on hydrogen derived from fossil-based processes. Gävleborg county presents favorable conditions for the integration of the boosting cooperation between offshore wind and green hydrogen in the regional industrial grid, potentially becoming a world-leading example of a cost-effective and effective energy transition towards a cleaner national energy industry. The regional business climate has proven favorable for initiatives aimed at reducing emissions through the implementation of hydrogen energy solutions. Projects under consideration include the installation of MW-scale electrolyzers and the construction of hydrogen refueling stations, with a focus on sectors that currently use or will use hydrogen in the future, such as hydrogen-powered cargo trucks. Table 4 illustrates the plans of various companies currently operating within the region:

Table 4 Gävleborg hydrogen-related plans

	Location	Company	Service	Electrolyzer (MW)
1	Borlänge	Maserfrakt	Electrolyzer + HRS	-
2	Hofors	Ovako	Electrolyzer + HRS	17
3	Sandviken	Linde Gas	Electrolyzer + HRS	1
4	Gävle	Gävle Hamn	Electrolyzer + HRS	3

Regarding offshore wind energy, over ten projects have been planned in this region due to ideal shallow seabed depths for a cheap deployment of bottom fixed offshore tech, highly potential wind resources exceeding most of the locations around the EU, and a foreseeable increase in the electricity demand, by 25 percent already by 2025 and by 50–65 percent by 2030, to meet the foreseeable electrified processes, such as green hydrogen electrolyzer requirements or power e-mobility [64]. Among all the plans in the pipeline, Svea Vind Offshore and WPD are the companies with the most promising projects for deploying the first offshore wind farm in the region. Table 5 provides a summary of the available information on the proposed wind farm plans along the Gävleborg coast, with estimated completion dates by 2030 and later.

¹ Magnitude order of the proposed wind farm power capacity.

² Preliminary approximate distance to Swedish mainland, willing to change with consultations and trials.

Table 5 Offshore wind plans on the Gävleborg coast [57]

Project	Capacity ¹ (MW)	Distance to shore ² (km)	Main owner company
Sylen Offshore	5000	55	Svea Vind Offshore AB
Eystrasalt	4000	60	WPD AG
Fyrskeppet	2800	45	WPD AG
Gretas Klackar I	1800	10	Svea Vind Offshore AB
Olof Skötkonung	1750	25	Deep wind offshore
Storgrundet	1000	10	WPD AG
Najaderna	1000	15	Eolus Vind AB
Gretas Klackar II	600	25	Svea Vind Offshore AB
Utposten II	500	15	Svea Vind Offshore AB
Utposten I	260	8	Svea Vind Offshore AB

The growing interest in the Gävleborg coast as a potential site for offshore wind projects demonstrates the potential for business growth in this Baltic Sea area, looking for taking advantage of the future electrification of Mid-Sweden hard-to-abate sectors. The gathered information in Table 5 has been analyzed presenting different patterns; for the sake of reaching the report purpose, different planned offshore wind farm features has been proposed regarding installed capacity (Capacity 1 = 4000 MW, Capacity 2 = 1750 MW, Capacity 3 = 600 MW) and distance to shore (Location 1 = 15 km, Location 2 = 50 km), as reflected in Figure 4.

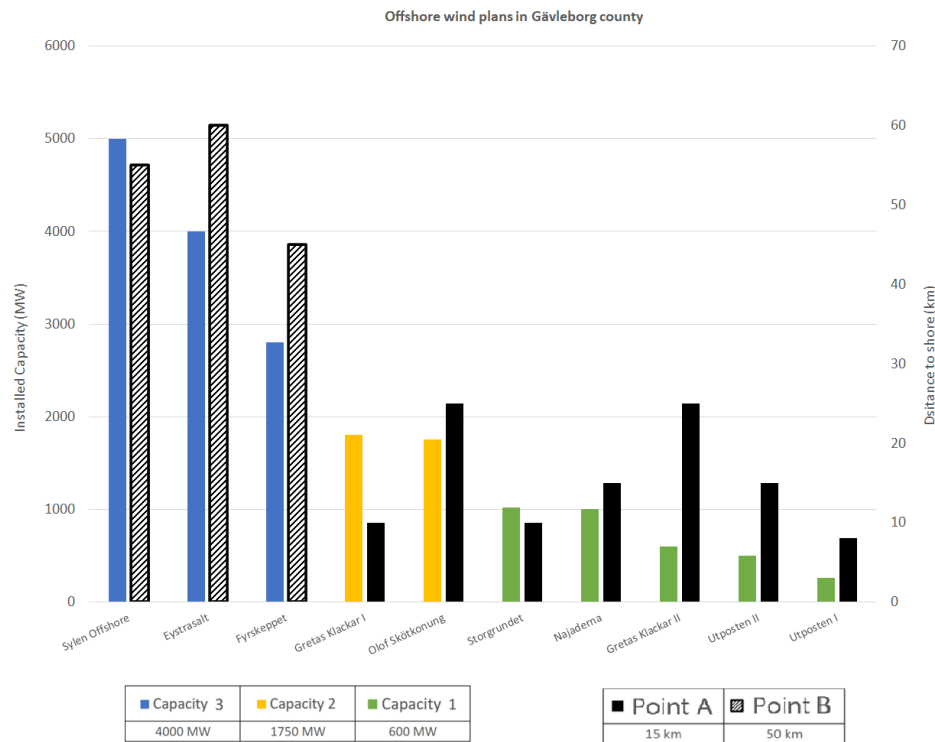


Figure 4 Offshore wind plans on the Gävleborg coast with respect to capacity and distance

The interested companies adopt different approaches based on their prospects on the regional economic and technical potential. This case study, conducted along the Gävleborg coast, includes three

¹ Magnitude order of the proposed wind farm power capacity.

² Preliminary approximate distance to Swedish mainland, willing to change with consultations and trials.

distinct designs that facilitate the analysis and examination of the prospects of companies operating in this area:

- Design 1: Capacity 1, Point A (600 MW, 15 km)

The most promising offshore wind farms in the short-term looking for supplying energy to shore by the end this decade, for either inject electricity to the grid or produce green hydrogen. Projects such as Utspoten II by Svea Vind Offshore, or Storgrundet by WPD AG are the most advanced in the complex and time-consuming legal process involving application for several different permits and notifications, as well as consultations with concerned authorities, organizations, and individuals. For instance, both projects plan to supply electricity for large scale electrolyzes in order to provide the required cost-effective hydrogen in the region [54].

- Design 2: Capacity 2, Point A (1750 MW, 15 km)

By the early 2030s, offshore wind plants along Gävleborg's coast are planning to install bigger offshore wind farms consisting of over 100 turbines. The primary goal of these projects is to produce enough electricity to cover the current electricity demand of Gävleborg and potentially meet future regional energy requirements for households, industry, and transport.

- Design 3: Capacity 3, Point B (4000 MW, 50 km)

The proposed mega-projects aim to construct more than 200 turbines in far offshore locations, which are expected to have a significantly lower visual impact on the mainland compared to other designs [57]. This approach amplifies the complexities associated with deploying such an engineering solution, ranging from technical intricacies to legal considerations. These ambitious offshore wind farms are touted to be a significant milestone in the pursuit of Sweden's environmental targets for 2045 and may be regarded as projects of national importance [58].

The deployment of the offshore wind projects described in Table 5 will involve the installation of more than 1 000 wind turbines with an installed capacity of 18 GW, with the potential to supply approximately 70 TWh of electricity to the region annually, which is several times greater than the 5.4 TWh of current electricity consumption in the county [65]. However, it should be noted that the majority of these plans are currently in the initial stages of conception and planning and are awaiting political initiatives and technological advancements to reach a level of economic competitiveness against other countries with similar offshore conditions in the EU. Therefore, there is a need for the relevant authorities to support the development of these projects, and for the relevant industries to continue to invest in research and development. This will help to ensure the successful deployment of these offshore wind projects and contribute to the growth of the region's renewable energy sector.

Table 6 sums up the conditions selected for each design trying to make a representative vision of the offshore wind projected plans on the coast. This study will first address the following three different voltage configurations to each design and next discuss and examine different alternatives:

Table 6 Case study designs' characteristics

	Wind farm nominal power	Distance to Shore	Technology selection	Voltage
Design 1	600 MW	15 km	HVAC	36 kV
Design 2	1750 MW	15 km	HVAC	110 kV
Design 3	4000 MW	50 km	HVDC	320 kV

5. Results

This section provides an analysis of the wind resource potential in two offshore locations within the region. The objective of this study is to present a comprehensive view of the potential for offshore wind-to-hydrogen production, including an evaluation of various offshore wind farms dedicated to hydrogen production varying the energy transmission configuration. Additionally, the environmental impact of the offshore wind farms is assessed. The results of this research offer valuable insights for policymakers and stakeholders interested in renewable energy and its potential for mitigating climate change and contribute to the growing body of knowledge on renewable energy.

5.1 Wind resource potential

The wind assessment analysis generated diverse results to assess the viability of renewable energy resources in the designated sites. This includes statistical metrics for wind resource characterization, specific parameters of Weibull's distribution curve, as well as energy and power production estimations. On the one hand, the location A presents an average and median velocity of 7.8 m/s and 7.6 m/s with a maximum value collected of nearly 26.5 m/s and Weibull parameters of $c=9.1$ m/s and $k=2.4$. On the other hand, location B presents an average and median velocity of 8.6 m/s and 8.4 m/s with a maximum value collected of nearly 27 m/s and Weibull parameters of $c=10.1$ m/s and $k=2.4$. The following wind potential results at Table 7 were used for the completion of the wind-to-hydrogen calculations:

Table 7 Case study wind resource potential

	Annual energy recovered (kWh/m ²)	Average power recovered (W/m ²)
Location A	1624.4	186.3
Location B	1974.0	225.3

5.2 Hydrogen production

The hydrogen production calculated in this section uses the parameters presented in the Methods chapter and the outputs from Table 7, assuming reactive compensation in the energy losses through the electricity transportation to shore. Table 8 presents the final results depending on the layout, calculated as follow:

- Result 1: Number of wind turbines, based on the nominal wind farm power and the peak power of the selected 15MW case study turbine.
- Result 2: Result 1 times the swept area of a wind turbine unit.
- Result 3: Percentage of power losses regarding the voltage selection, account for losses in transformers, power electronics and transportation through cables.
- Result 4: Represents the average output power from a certain layout, making use of the above presented average power recovered per swept square meter (W/m²) and the number of total covered swept area (Result 2). In turn, Result 5 applies the energy losses for the selected layout.
- Result 6: Applying the linear-scaling procedure of Table 2. can be calculated the hydrogen producing of a certain electrolyzer power equal to Result 4.
- Result 7: Represents the energy output from a certain design in a whole year, making use of the above presented average energy recovered per swept square meter (kWh/m²) and the number of total covered swept area (Result 2). In turn, Result 8 applies the energy losses for the selected layout.

- Result 9: Hydrogen production in a day in average, applying the energy ratio presented in Figure 2 to the energy arriving to shore
- Result 10: Compare energy and power-wise hydrogen production and return the most restrictive value.

Table 8 Final study results

		Design 1	Design 2	Design 3
	Power capacity wind farm (MW)	600	1750	4000
1	Number of wind turbines	40	117	267
2	Total swept area	1 749 720	5 117 931	11 679 381
3	Power losses transportation	2.79%	6.48%	3.61 %
Power-Wise				
4	Average output power (MW)	326	954	2176
5	Power to shore (MW)	319	892	2098
6	Hydrogen production (kgH ₂ /day)	136 700	384 800	905 000
Energy-wise				
7	Energy production per year (TWh/year)	2,86	8.35	19.06
8	Energy to shore (TWh/year)	2,77	7.81	18.37
9	Hydrogen production (kgH ₂ /day)	149 200	420 000	990 000
10	Hydrogen production (kgH ₂ /day)	136 700	384 800	905 000

The study results make use of three transmission technologies trying to represent the different options that can apply in the proposed wind farms, as information such as the voltage level or the transmission technology is not available in the literature. Nonetheless, Figure 5 illustrate the variation in hydrogen production for each preestablished layout, depending on whether alternating current with or without reactive compensation, or direct current at different voltage levels is used, highlighting the values represented in the results section (Table 8):

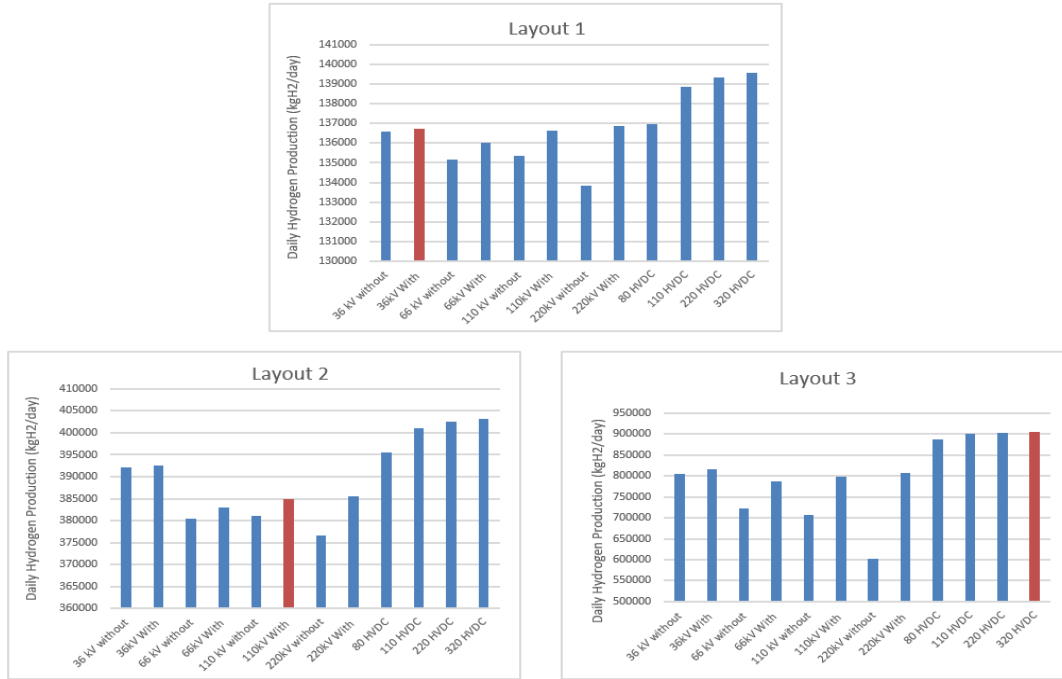


Figure 5 Hydrogen production depending on transmission tech and voltage level

5.3 Energy transmission losses

This research report has limited the study of the offshore wind resources in Gävleborg's waters by establishing three designs with only two locations. The energy transmission losses and thus the hydrogen production onshore will vary inherently with the wind farm distance to shore and the technology selected. Therefore, Figure 6 represents a sensitivity analysis regarding distance to shore and energy transmission set up illustrating a tendency of energy losses which remains constant with every layout. Distances lower than 10 kilometers show a clear advantage for HVAC set ups using voltage levels produce at the wind farm, such as 36 kV (Section 2.2.1), and thus without using offshore transformers. Distances between 10 and 15 kilometers present a large variety of options below 5% losses and most promisingly the planned projects in Gävleborg will focus primarily on the economical aspect in these range as the technical aspects are so similar regardless the transmission set up selected. Nevertheless, as the projects gets further from shore there are more detectable differences between technologies where the most promising are HVAC with reactive compensation and HVDC, which their selection will rely on either technical aspect regarding energy losses and in-depth economic studies.

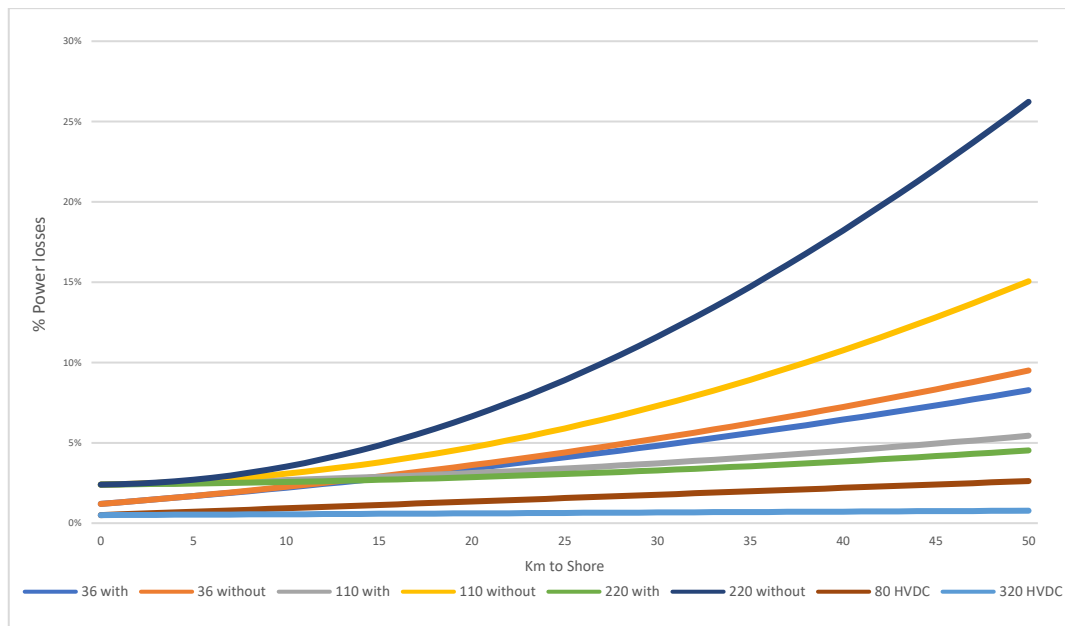


Figure 6 Power losses variation with energy transmission setup and distance to shore

5.4 GHG emission assessment

This report analyzes the possible environmental consequences resulting from the complete integration of different designs for hydrogen production. To conduct a fair comparison, the impact of off-shore wind energy has been evaluated against the use of electricity from the Swedish grid mix or the process of steam methane reforming. The study aims to identify the optimal approach for hydrogen production that minimizes its environmental impact.

Table 9 presents the CO₂ emissions reductions resulting from the production of hydrogen for each design specified in Table 8. These reductions are evaluated by employing the ratios presented in Table 3 for the corresponding processes, which allows for an assessment of the environmental impact of hydrogen production.

Table 9 GHG emission by hydrogen production process

	Design 1	Design 2	Design 3
Hydrogen production (kgH ₂ /day)	136 700	384 800	905 000
Emissions by process (kgCO ₂ /day)			
Steam methane reforming	1 658 000	4 667 000	10 977 000
Electrolysis - Swedish grid mix energy	327 000	922 000	2 169 000
Electrolysis - Offshore wind	83 000	235 000	553 000

6. Discussion

The results of this study are primarily governed by the wind resources found offshore along the Gävleborg coast. These resources can significantly impact the feasibility and viability of offshore wind energy production. The wind conditions, such as wind speed and direction, play a crucial role in determining the optimal turbine design, placement, and overall energy output. Furthermore, the outcomes may vary slightly depending on the chosen energy transmission technology and voltage. The transmission technology selected can impact the cost, efficiency, and overall performance of the offshore wind energy system. Factors such as cable type, distance to shore, and interconnection with the grid can also influence the final outcome of the study. In addition to wind resources and transmission technology, several other standard parameters can be easily replicable in similar studies, such as wind turbine selection and related power efficiency curve calculation which are crucial factors that can significantly impact the overall energy output of the system. Accurate calculation of hydrogen production ratios is also essential, as it directly impacts the potential for green hydrogen production.

The findings of this study align with the energy production estimation previously published by various developers, with minor variations resulting from differences in the study location and methodology used to assess the wind resource potential. In addition to electricity generation capacity, this study has highlighted the potential for offshore wind farms to produce hydrogen on a daily basis from the electricity generated. This presents exciting opportunities for businesses and innovation in the region in the years to come. As the demand for renewable energy sources continues to grow, offshore wind farms have the potential to play a significant role in meeting this demand. The production of hydrogen from offshore wind farms could also have far-reaching implications for industries such as transportation, where hydrogen fuel cells are being developed as a clean energy alternative to traditional fossil fuels. Overall, the findings of this study support the continued development of offshore wind farms as a renewable energy source with the potential to produce both electricity and hydrogen. While there may be challenges to overcome in terms of infrastructure and implementation, the benefits of offshore wind farms make them an attractive option for meeting the world's energy needs in a sustainable way. As such, further research and development in this area is crucial to unlocking the full potential of offshore wind farms as a source of clean and renewable energy.

Moreover, the results presented in the Table 8 are aligned with some of the current offshore wind to hydrogen projects proposed in the region, such as conjunction between WPD and the French producer Lhyfe which announced the daily production up to 240 000 kilograms of hydrogen coupled to the 1GW Storgrundet offshore wind farm leading to a ratio of around 0.25 tons of daily hydrogen production per offshore wind MW capacity in Gävleborg region [66]. Furthermore, some results verification has been done in this study to confirm the preciseness of the wind study, comparing the performed resource wind power density analysis with the same value at New European Wind Atlas database, presenting highly similar results.

It is worth mentioning that in the final results shown in Table 8, there are higher energy losses in the Design 2 than in 1 despite the fact of using higher voltage with reactive compensation. This effect is directly related to the higher farm capacity and the related extra losses added by the transformers, explained in Section 3.3. In this direction, the phenomenon of higher hydrogen production at 36kV (Figure 5) compared to higher voltages is closely associated with transformer losses. This is due to the use of offshore transformers are not required for the 36kV voltage output from the turbines to transport energy to shore, introduced in Section 2.2.1. However, this alternative may not be cost-effective for larger wind farms due to the increased on the number of required cables and its associated investment costs. Therefore, other options should be explored for larger wind farm capacities.

Based on the results of the environmental impact study included in this report, it has been determined that utilizing the Swedish grid mix or direct offshore wind energy to power the electrolyzer has minimal impact on greenhouse gas emissions reduction. Additionally, it is anticipated that the Swedish grid mix will become even more environmentally friendly in the future, resulting in a smaller discrepancy between the two methods.

Due to the magnitude of the report and the type of study, it is worth enumerating some limitations in this paper. Regarding the wind resource a specific study is complex work that requires years of onsite data collection at different heights, being at least one of these measurements at $2/3$ of the hub's altitude. It is a usual practice to obtain data every 2 seconds and do an average calculation of every 10 minutes. To perform the energy losses calculations in line with the report's objective some assumptions has been done regarding the reactive compensation assessment. The methodology conducted used the same cable schema as in Figure 3 regardless the implementation of reactive compensation, assuming that the power at the end of the line arrived with unit power factor. Moreover, the typical transformer and power electronics energy losses selected from the literature are consistent through most of the studies of this regard, thus the error added with this assumption is assumable.

7. Conclusion

The county of Gävleborg, situated in the heart of Sweden, is well-positioned to spearhead the transition towards a hydrogen-based industry. With its rich history in steel and paper manufacturing, the region has been using hydrogen for a long time, giving it valuable expertise in the field. The experience gained from using hydrogen in these industries makes Gävleborg a natural fit for advancing the use of hydrogen in other sectors. Moreover, the region boasts significant offshore wind resources, which are capable of generating large amounts of low-cost electricity and hydrogen. Offshore wind farms have the added advantage of being planned near the shore and in shallow waters.

This study outlines three different design options, ranked in order of most promising for the upcoming years to future mega-project plans exceeding a gigawatt of power that may be deployed once the technology has matured and Sweden's knowledge in the offshore wind industry has increased. The report focuses on a technological study of the different components used in the offshore wind-to-hydrogen industry, including wind turbine foundations, electrolyzers, and energy transmission technologies. The Gävleborg coast has a shallow seabed that is suitable for utilizing offshore wind resources with bottom fixed foundations, making it a cost-effective area for investment. The report has selected PEM technology for electrolyzer technology due to its favorable characteristics when connecting to variable electricity inputs and its large prospects in application in renewable energy plants. However, there is a controversial debate regarding energy transmission to shore, as different set-ups can be proposed depending on the type of electrical current (alternating or direct current) and voltage levels, or whether reactive compensation is used. The study shows the potential of HVDC technology as the option that transmits more energy to shore, with greater potential compared to other technologies when the wind farm has greater capacity and is located further from the shore. However, the power electronics of this configuration make it the most expensive set-up, and its selection will be determined by in-depth techno-economic study. Another attractive alternative is the usage of the wind turbine output voltage level, which implies fewer energy losses due to the non-usage of transformers before the energy transmission to shore. However, this setup is less likely to be feasible as the wind farm capacity increases, as the low voltage level requires more cables and incurs higher investment costs. The study emphasizes the importance of reactive power compensation as the project uses higher voltage levels and is located further from the shore. Despite the assumptions made to achieve the research report's goal, the study has identified potential set-ups that can be applied to each layout.

- Design 1: High voltage alternating current with voltage levels of 36-66 kV are suitable for offshore wind farms located near the shore in Gävleborg, particularly for those with relatively low-capacity power. The proximity of the wind farms to the shore makes this voltage level advantageous due to the lower energy drop during transmission through cables and the non-usage of offshore transformers. Even more, wind farms with low-capacity power are more likely to accept the increased number of cables using low voltage levels.
- Design 2: These projects will require higher voltage levels through the energy transmission due to the increased wind farm capacity power and thus, the usage of offshore transformers. This design is more likely to use HVAC with voltage levels over the wind turbine output, such as 110 or 220 kV. The usage of reactive compensation relies upon a deeper techno-economical study.
- Design 3: Projects falling in this category have a long-term outlook, and the technologies used will mature and undergo significant advancements over the years. Currently, the most promising setups for the far distance to shore and high-power capacity are HVAC with reactive compensation and higher voltage levels, or HVDC technology.

This case study examines three different offshore wind designs, namely Designs 1 to 3, with energy production representing 50%, 140%, and 340% of the current electricity consumption in Gävleborg county. However, as the electrification of the economy is expected to increase to combat climate change, this percentage is likely to decrease. Completion of these projects will make Gävleborg a net exporter of inexpensive energy to neighboring regions and countries, inherently attracting business investment in the region. To meet the demand for hydrogen, a single completion of a wind farm with the characteristics of the design 1 entirely dedicated to hydrogen production, has the potential

to cover almost all the current hydrogen consumption in the country. However, this hydrogen demand is subject to change as industries adopt cleaner ways to produce and consume hydrogen. Thus, comprehensive studies of the energy system will be required to determine the number of offshore wind farms worth building and which designs are most likely to contribute to national sustainability development

To conclude, a broader perspective can be given to this report. The humanity has been extracting energy resources from the sea for the last decades with oil factories; with the future focus on reducing fossil fuel consumption, this offshore energy extraction is called to be based on wind energy. The deployment of offshore wind to hydrogen projects in areas of high wind potential can be a game changer in the energy sector, where cheap offshore hydrogen production can turn this energy carrier not a real and available solution in sectors that are difficult to decarbonize, such as ship or aircraft propulsion. Hydrogen production at a big scale has a geopolitical and economic importance to stop depending on the main fossil fuel suppliers; furthermore, countries with high renewable energy production can turn into hydrogen exporter in the coming decades.

This project is in line with the Sustainable Development Goals included in the United Nations 2030 Agenda; clean and affordable energy production, innovative industrial perspective, decent work, and economic growth are some of the proposed challenges that this thesis aims to overcome.

8. References

- [1] D. Qin *et al.*, “Technical Summary. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I,” 2013.
- [2] United Nations. "Sustainable Development Goals." United Nations, n.d., <https://www.un.org/sustainabledevelopment/sustainable-development-goals/>. (accessed 14 Apr. 2023).
- [3] Jepsen, H., Monjane, L., Gueye, M. K., & Hynes, W. (Eds.). (2021). *Negotiating the Paris Agreement: The Insider Stories*. Cambridge University Press.
- [4] “Hydrogen – Analysis – International Energy Agency. IEA (2021).” <https://www.iea.org/reports/hydrogen> (accessed Oct. 12, 2022).
- [5] “Net Zero by 2050 – Analysis – International Energy Agency. IEA (2021).” <https://www.iea.org/reports/net-zero-by-2050> (accessed Oct. 13, 2022).
- [6] Hydrogen: Europe’s Industry rolling out hydrogen projects on massive scale. https://single-market-economy.ec.europa.eu/news/hydrogen-europes-industry-rolling-out-hydrogen-projects-massive-scale-2021-11-30_en (accessed Oct. 13, 2022).
- [7] S. Sorrell, “Understanding barriers to energy efficiency,” *The Economics of Energy Efficiency*, pp. 11–62, 2004.
- [8] International Energy Agency. IEA, “The Future of Hydrogen: Seizing today’s opportunities,” *IEA Publications*, no. June, p. 203, 2019.
- [9] Fuel Cells and Hydrogen 2 Joint Undertaking, *Hydrogen roadmap Europe : a sustainable pathway for the European energy transition*, Publications Office, 2019, <https://data.europa.eu/doi/10.2843/341510>
- [10] “Electrolysers – Analysis - International Energy Agency. IEA.” <https://www.iea.org/reports/electrolysers> (accessed Oct. 15, 2022).
- [11] Group THEMA Consulting, “Offshore wind development key to meet Sweden’s climate and growth targets,” no. October, 2021.
- [12] Energimyndigheten & Fossilfritt Sverige. (2019). *Strategi för fossilfri konkurrenskraft*
- [13] “Sweden tops France as Europe’s largest net power exporter | Reuters.” <https://www.reuters.com/business/energy/sweden-tops-france-europes-largest-net-power-exporter-2022-08-10/> (accessed Oct. 19, 2022).
- [14] “Levelised Cost of Hydrogen | FCH Observatory.” <https://www.fchobservatory.eu/observatory/technology-and-market/levelised-cost-of-hydrogen-grid-connected-electrolysis> (accessed Oct. 19, 2022).
- [15] “Wind farm costs – Guide to an offshore wind farm.” <https://guidetoanoffshorewindfarm.com/wind-farm-costs> (accessed Oct. 19, 2022).
- [16] “Offshore hydrogen production enables far-offshore wind deployment.” <https://hydrogentechworld.com/offshore-hydrogen-production-enables-far-offshore-wind-deployment> (accessed Oct. 19, 2022).

- [17] “Invest in Gävleborg. (n.d.). Gävleborg wind energy industry opportunities.” <https://www.investingavleborg.com/business-areas/renewable-energy/wind-energy/>
- [18] IPCC, *Climate Change 2022: Mitigation of Climate Change*. in Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press (In Press), 2022. doi: 10.1017/9781009157926.
- [19] B. Purvis, Y. Mao, and D. Robinson, “Three pillars of sustainability: in search of conceptual origins”, doi: 10.1017/s0376892900011449.
- [20] Hinrichsen, D. (2006). Trends and future challenges for U.S. national ocean and coastal policy. *Coastal Management*, 34(1), 5-22. <https://doi.org/10.1080/08920750500365190>
- [21] DNV GL. (2022). Energy Transition Outlook 2022: A global and regional forecast to 2050. <https://eto.dnvgl.com/2022/>
- [22] “H-BLIX Offshore wind vessel availability until 2030: Baltic Sea and Polish perspective-Offshore wind vessel availability until 2030: Baltic Sea and Polish perspective Final Report,” 2022, Accessed: Jan. 27, 2023. [Online]. Available: www.h-blix.com.pl
- [23] “Bottom fixed offshore wind - WEAMEC EN.” <https://www.weamec.fr/en/mre-technologies-weamec/bottom-fixed-offshore-wind/> (accessed Jan. 27, 2023).
- [24] “ENERGY TRANSITION OUTLOOK 2022 A global and regional forecast to 2050”.
- [25] G. Stewart and M. Muskulus, “A Review and Comparison of Floating Offshore Wind Turbine Model Experiments,” *Energy Procedia*, vol. 94, pp. 227–231, 2016, doi: 10.1016/J.EGYPRO.2016.09.228.
- [26] European Commission, “Study on Baltic offshore wind energy cooperation under BEMIP : final report,” *Directorate-General for Energy*, 2019.
- [27] International Renewable Energy Agency, “Global Energy Transformation: A Roadmap to 2050 (2019 Edition),” 2019, Accessed: Jan. 30, 2023. [Online]. Available: www.irena.org
- [28] M. R. Islam, Y. Guo, and J. Zhu, “A transformer-less compact and light wind turbine generating system for offshore wind farms,” *PECon 2012 - 2012 IEEE International Conference on Power and Energy*, pp. 605–610, 2012, doi: 10.1109/PECON.2012.6450285.
- [29] “Alternating current - Wikipedia.” https://en.wikipedia.org/wiki/Alternating_current (accessed Jan. 31, 2023).
- [30] G. Liu, M. Fan, P. Wang, and M. Zheng, “Study on Reactive Power Compensation Strategies for Long Distance Submarine Cables Considering Electrothermal Coordination,” 2021, doi: 10.3390/jmse9010090.
- [31] W. Wiechowski and P. Borre Eriksen, “Selected studies on offshore wind farm cable connections - challenges and experience of the Danish TSO,” *IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century*, 2008.
- [32] “What Makes Up The Cost Of A Cable? Are Approved Cables More Expensive? - MEP Middle East.”

- <https://www.mepmiddleeast.com/business/75546-what-makes-up-the-cost-of-a-cable-are-approved-cables-more-expensive> (accessed Mar. 07, 2023).
- [33] M. Guarnieri, "The Alternating Evolution of DC Power Transmission [Historical]," *IEEE Industrial Electronics Magazine*, vol. 7, 2013, doi: 10.1109/MIE.2013.2272238.
 - [34] "Dogger Bank HVDC connection." <https://www.hitachienergy.com/se/sv/about-us/case-studies/dogger-bank> (accessed Feb. 06, 2023).
 - [35] "Hornsea Project One, Offshore Wind Farm, North Sea." <https://www.power-technology.com/projects/hornsea-project-one-north-sea/> (accessed Feb. 06, 2023).
 - [36] "Kriegers Flak Combined Grid Solutions (KF CGS) HVDC." <https://www.hitachienergy.com/about-us/case-studies/kriegers-flak-combined-grid-solutions--kf-cgs--hvdc> (accessed Feb. 06, 2023).
 - [37] N. G. Hingorani, "High-voltage DC transmission: a power electronics workhorse," *IEEE Spectr*, vol. 33, no. 4, pp. 63–72, 1996, doi: 10.1109/6.486634.
 - [38] "World Energy Transitions Outlook 2022." <https://www.irena.org/Digital-Report/World-Energy-Transitions-Outlook-2022> (accessed Feb. 02, 2023).
 - [39] O. S. Ibrahim, A. Singlitico, R. Proskovics, S. McDonagh, C. Desmond, and J. D. Murphy, "Dedicated large-scale floating offshore wind to hydrogen: Assessing design variables in proposed typologies," *Renewable and Sustainable Energy Reviews*, vol. 160, May 2022, doi: 10.1016/J.RSER.2022.112310.
 - [40] "EUROPE'S FIRST MAJOR GREEN HYDROGEN CORRIDOR". <https://www.lamoncloa.gob.es/presidente/actividades/Documents/2022/091222-H2MED.pdf>
 - [41] "OX2 to investigate the possibility to develop offshore hydrogen pipeline in the Baltic Sea - OX2." <https://www.ox2.com/news-room/press-releases-news/2022/ox2-to-investigate-the-possibility-to-develop-offshore-hydrogen-pipeline-in-the-baltic-sea/> (accessed Feb. 02, 2023).
 - [42] "Hywind Tampen - Equinor." <https://www.equinor.com/energy/hywind-tampen> (accessed Feb. 02, 2023).
 - [43] "Power-to-Gas / Wind2Hydrogen: Gas Connect." <https://www.gas-connect.at/ueber-erdgas/erdgastechnologien/power-to-gas-wind2hydrogen> (accessed Feb. 02, 2023).
 - [44] O. S. Ibrahim, A. Singlitico, R. Proskovics, S. McDonagh, C. Desmond, and J. D. Murphy, "Dedicated large-scale floating offshore wind to hydrogen: Assessing design variables in proposed typologies," *Renewable and Sustainable Energy Reviews*, vol. 160, May 2022, doi: 10.1016/J.RSER.2022.112310.
 - [45] M. A. Semeraro, "Renewable energy transport via hydrogen pipelines and HVDC transmission lines," *Energy Strategy Reviews*, vol. 35, May 2021, doi: 10.1016/J.ESR.2021.100658.
 - [46] International Energy Agency. IEA, "World Energy Outlook 2022," 2022, Accessed: Feb. 06, 2023. [Online]. Available: www.iea.org/t&c/

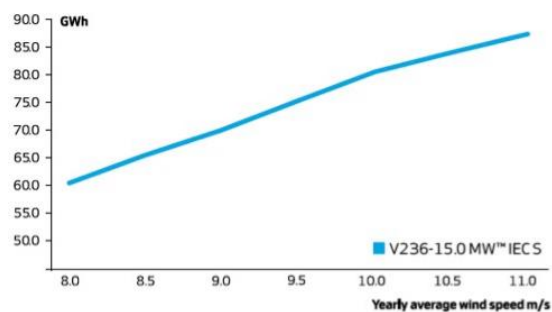
- [47] International Energy Agency. IEA, “Making the breakthrough: Green hydrogen policies and technology costs,” 2021, Accessed: Feb. 03, 2023. [Online]. Available: www.irena.org
- [48] J. & T. Thomas. Brauns, “Alkaline Water Electrolysis Powered by Renewable Energy: A Review. ,” 2020.
- [49] “Electrolysers – Analysis - International Energy Agency. IEA.” <https://www.iea.org/reports/electrolysers> (accessed Feb. 06, 2023).
- [50] G. Calado and R. Castro, “Hydrogen Production from Offshore Wind Parks: Current Situation and Future Perspectives,” *Applied Sciences*, vol. 11, no. 12, p. 5561, Jun. 2021, doi: 10.3390/app11125561.
- [51] P. Zandén Kjellén, “Hydrogen and heavy trucks in Gävleborg”.
- [52] “NEW EUROPEAN WIND ATLAS -.” <https://www.neweuropeanwindatlas.eu/mission> (accessed Feb. 15, 2023).
- [53] J. Luis Blay Pomar., “Offshore wind to hydrogen for powering port land mobility. Case study in Port of Valencia. Student thesis, Advanced level (Master degree, one year), 15 HE Energy Systems Master Programme in Energy Systems”.
- [54] K. Jayasinghe, “POWER LOSS EVALUATION OF SUBMARINE CABLES IN 500MW OFFSHORE WIND FARM,” 2017.
- [55] H. : Jimmie, E. Ämnesgranskare, J. Forslund, E. Andrésdóttir, A. Bråve, and S. Särnblad, “Teknisk-naturvetenskapliga fakulteten Uppsala universitet, Utgivningsort Uppsala Reactive power compensation of the electricity grid with large-scale offshore wind farms in Sweden”.
- [56] A. Papadopoulos, “Modeling of Collection and Transmission Losses of Offshore Wind Farms for Optimization Purposes,” *Electrical Engineering, Mathematics and Computer Science*, 2015.
- [57] J. Larsson, “Examensarbete 30 hp Maj 2021 Transmission Systems for Grid Connection of Offshore Wind Farms HVAC vs HVDC Breaking Point”, Accessed: Feb. 21, 2023. [Online]. Available: <http://www.teknat.uu.se/student>
- [58] K. Jayasinghe, “POWER LOSS EVALUATION OF SUBMARINE CABLES IN 500MW OFFSHORE WIND FARM,” 2017.
- [59] S. Rodrigues *et al.*, “A Multi-Objective Optimization Framework for Offshore Wind Farm Designs and Electric Infrastructures,” 2016, doi: 10.3390/en9030216.
- [60] A. Mehmeti, A. Angelis-Dimakis, G. Arampatzis, S. J. McPhail, and S. Ulgiati, “Life Cycle Assessment and Water Footprint of Hydrogen Production Methods: From Conventional to Emerging Technologies”, doi: 10.3390/environments5020024.
- [61] S. Lundberg, “Comparative LCA of Electrolyzers for Hydrogen Gas Production SCHOOL OF ARCHITECTURE AND THE BUILT ENVIRONMENT,” 2019.
- [62] T. International Renewable Energy Agency, “GREEN HYDROGEN COST REDUCTION SCALING UP ELECTROLYSERS TO MEET THE 1.5°C CLIMATE GOAL H 2 O 2,” 2020, Accessed: Feb. 08, 2023. [Online]. Available: www.irena.org/publications
- [63] “Roadmap 2040”. <https://swedishwindenergy.com/wp-content/uploads/2021/01/Roadmap-2040-ENG-rev-2020.pdf>

- [64] B. Andrea, “Elkraftförsörjning i Gävleborg,” 2021.
- [65] “Electricity energy, consumption by county - Regionfakta.” <https://www.regionfakta.com/vastra-gotalands-lan/in-english-energy/electricity-energy-consumption-by-county/> (accessed Feb. 14, 2023).
- [66] “WPD and Lhyfe build 600 MW electrolyser in Sweden - energate messenger.com.” <https://www.energate-messenger.com/news/221602/wpd-and-lhyfe-build-600-mw-electrolyser-in-sweden> (accessed Mar. 06, 2023).

Appendix A

Main characteristics of the offshore wind turbine V236-15.MW manufactured by Vestas.

POWER REGULATION		Pitch regulated with variable speed
OPERATING DATA		
Rated power		15,000 kW
Cut-in wind speed		3 m/s
Cut-out wind speed		30 m/s
Wind class		IEC S or S,T
Standard operating temperature range	from -10°C to +25°C* with a de-rating interval from +25°C to +45°C	
	*high ambient temperature variant available	
SOUND POWER		
Maximum		118dB(A)
ROTOR		
Rotor diameter		236 m
Swept area		43,742 m²
Aerodynamic brake		three blades full feathering
ELECTRICAL		
Frequency		50/60Hz
Converter		full scale
GEARBOX		
Type		three planetary stages
TOWER		
Hub height		site-specific



Appendix B

The energy losses data has been collected from the marine products datasheet of the Chinese company ZTT group, one of the largest advanced manufacturing enterprises in China and is listed among the Top 500 Chinese Enterprises.

	HVAC			
Voltage	36	66	110	220
Ampacity (A)	537	419	795	809
Resistance (Ω/km)	0,0614	0,0778	0,0272	0,0268
Capacitance (F/km)	0,000000234	0,000000167	0,000000226	0,000000168
Inductance (H/km)	0,000374	0,000406	0,000368	0,000402

	HVDC			
Voltage	80	160	220	320
Ampacity (A)	1001	1387	1822	2030
Resistance (Ω/km)	0,0339	0,0181	0,0108	0,0087

Research Report Series

1. Work Values among Swedish Male and Female Students. Katarina Wijk. Department of Occupational and Public Health Sciences 2011.
2. The Doll, the Globe and the Boomerang - Chemical Risks in the Future, Introduced by a Chinese Doll Coming to Sweden. Ernst Hollander. Department of Business and Economic Studies 2011.
3. Divergences in descriptions of the internal work environment management, between employees and the management, a case study. Katarina Wijk and Per Lindberg. Department of Occupational and Public Health Sciences 2013.
4. Energy and nutrients from horse manure - Life-cycle data inventory of horse manure management systems in Gävleborg, Sweden. Jay Hennessy and Ola Eriksson. Department of Engineering and Sustainable Development 2015.
5. Prospects for biodiesel in Gävleborg County: Feedstock and production. Pontus Norell. Department of Building Engineering, Energy Systems and Sustainability Science 2019.
6. Biogas value chain in Gävleborg: Feedstock, production and use. Muhammad Arfan. Department of Building Engineering, Energy Systems and Sustainability Science 2019.
7. Social inclusion through segregation? Liya Kalinnikova Magnusson and Jeremias Rosenqvist. Department of Educational Sciences 2020.
8. Exploring the Viability of Electric Vehicles: Sustainable Transportation in Gävleborg. Peder Kjellén and Katja Tasala Gradin. Department of Building Engineering, Energy Systems and Sustainability Science 2020.
9. Might high-ability pupils be teachers' headache: the "justice" in rating? Cornelia Wulff Hamrin, Kimmo Sorjonen, Chris Magnusson. Department of Educational Sciences 2021.
10. Exploring the Viability of Electric Vehicles: Sustainable Transportation in Gävleborg. Peder Zandén Kjellén. Department of Building Engineering, Energy Systems and Sustainability Science 2021.
11. Assessment of offshore wind transmission technologies for green hydrogen production: Case study in Gävleborg County, Sweden. Jose Luis Blay Pomar. Department of Building Engineering, Energy Systems and Sustainability Science 2023.

Published by:
Gävle University Press



Postal address: SE-801 76 Gävle, Sweden
Visiting address: Kungsbäcksvägen 47
Telephone: +46 26 64 85 00
www.hig.se