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Optimal operation and decentralized control of offshore DC grid with renewable energy sources

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ABSTRACT:

The transition to sustainable energy systems is critical for achieving global decarbonization targets, with offshore hydrogen production emerging as a promising solution to support carbon neutrality efforts. Offshore hydrogen systems, leveraging renewable energy sources such as wind and solar, are increasingly recognized for their potential to deliver scalable and sustainable energy solutions. This thesis focuses on the techno-economic evaluation of offshore hydrogen systems, emphasizing their technical feasibility and economic viability under varying environmental and infrastructural conditions.

A comprehensive literature analysis is conducted, to evaluate the best available techniques and possible configurations of such systems. The feasibility is considered through the key factors influencing the Levelized Cost of Hydrogen (LCOH) in offshore production, including infrastructure costs, storage, and transportation methods**.** Offshore hydrogen production incurs higher capital and operational costs as it requires desalination units, specialized electrolyzers, and robust marine infrastructure. Additionally, the choice between offshore and onshore storage, as well as transportation method, introduces complex trade-offs that directly impact hydrogen economics.

At the European level, the thesis examines the policy landscape and market development of renewable hydrogen, highlighting the gap between the EU's ambitious targets and current production capacity. Regulatory uncertainties, infrastructure limitations, and cost barriers hinder large-scale deployment, while national strategies vary in ambition and implementation. Key policy instruments, including carbon contracts for difference (CCfD), direct subsidies, and certification mechanisms, are assessed for their role in fostering a competitive hydrogen market.

Furthermore, this study presents case studies of four pioneering offshore green hydrogen projects—PosHYdon (Netherlands), Dolphyn (UK), H2Mare (Germany), and Gigastack (UK)—which offer valuable insights into feasibility, scalability, and sustainability. These projects illustrate innovative approaches to integrating renewable energy with hydrogen production, while addressing infrastructure and regulatory challenges.

By analysing the interplay between cost drivers, regulatory frameworks, and real-world case studies, this research provides a comprehensive understanding of the evolving offshore hydrogen sector. The findings highlight the necessity for coordinated policy support, technological advancements, and strategic infrastructure investments to ensure the economic viability and scalability of offshore hydrogen production.

KEYWORDS: Hydrogen, Renewable energy, Case studies, Levelized cost of hydrogen

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ABSTRACT:

Siirtymä kestävän energiajärjestelmän pariin on kriittinen globaalien hiilidioksidipäästövähennystavoitteiden saavuttamiseksi, ja merituulivoimaan perustuva vedyn tuotanto on nousemassa lupaavaksi ratkaisuksi hiilineutraaliuden edistämisessä. Merellä sijaitsevat vedyn tuotantojärjestelmät, jotka hyödyntävät uusiutuvia energialähteitä, kuten tuulta ja aurinkoenergiaa, tunnistetaan yhä enenevässä määrin skaalautuvien ja kestävien energiaratkaisujen ratkaisuiksi. Tämä diplomityö keskittyy kyseisten tuotantojärjestelmien teknillistaloudelliseen arviointiin, painottaen niiden teknistä toteutettavuutta ja taloudellista kannattavuutta vaihtelevissa ympäristö- ja infrastruktuuriolosuhteissa.

Työssä suoritetaan kattava kirjallisuusanalyysi, jolla arvioidaan saatavilla olevia parhaita tekniikoita ja mahdollisia järjestelmäkonfiguraatioita. Toteutettavuutta tarkastellaan keskeisten tekijöiden, kuten vedyn tasakustannusten (LCOH) määrittävien infrastruktuurikustannusten, varastoinnin ja kuljetusmenetelmien kautta. Merellä tapahtuva vedyn tuotanto aiheuttaa korkeammat pääoma- ja käyttökustannukset johtuen muun muassa suolanpoistoyksiköiden, erikoiselektrolysaattoreiden ja merirakenteiden tarpeesta. Lisäksi valinta offshore- ja onshore-varastoinnin välillä, sekä vedyn kuljetusmuodon valinta, vaikuttavat suoraan vedyn taloudelliseen kannattavuuteen.

Euroopan tasolla työ tarkastelee uusiutuvan vedyn poliittista toimintaympäristöä ja markkinoiden kehitystä, korostaen EU:n kunnianhimoisten tavoitteiden ja nykyisen tuotantokapasiteetin välistä kuilua. Sääntelyn epävarmuus, infrastruktuurirajoitteet ja kustannusesteet hidastavat laajamittaista käyttöönottoa, samalla kun kansalliset strategiat vaihtelevat kunnianhimon ja toteutuksen osalta. Keskeisiä poliittisia instrumentteja, kuten hiilisopimuksia (CCfD), suoria tukia ja sertifiointimekanismeja, arvioidaan niiden roolin osalta kilpailukykyisten vetymarkkinoiden edistämisessä.

Lisäksi tutkimuksessa esitellään neljä edistyksellistä offshore vihreän vedyn pilottihanketta PosHYdon (Alankomaat), Dolphyn (Iso-Britannia), H2Mare (Saksa) ja Gigastack (Iso-Britannia) joista saadaan arvokasta tietoa toteutettavuudesta, skaalautuvuudesta ja kestävyydestä. Nämä projektit havainnollistavat innovatiivisia tapoja yhdistää uusiutuva energia vedyn tuotantoon sekä ratkaista infrastruktuuriin ja sääntelyyn liittyviä haasteita.

Analysoimalla kustannustekijöiden, sääntelykehysten ja käytännön tapaustutkimusten välistä vuorovaikutusta, tämä tutkimus tarjoaa kattavan ymmärryksen kehittyvästä merivedyn tuotannonalasta. Tulokset korostavat tarvetta koordinoidulle poliittiselle tuelle, teknologisille edistysaskeleille ja strategisille infrastruktuuri-investoinneille, jotta offshore-vedyn tuotanto voidaan tehdä taloudellisesti kannattavaksi ja skaalautuvaksi.

KEYWORDS: vety, uusiutuva energia, tapaustutkimukset, vedyn tuotantokustannukset

Preface

The journey of writing this thesis has been both challenging and rewarding. Throughout this process, I have had the opportunity to deepen my understanding of offshore hydrogen production and apply the knowledge gained during my studies to a real-world problem.

I would like to express my gratitude to my thesis' supervisor, Professor Xiaoshu Lü, for the opportunity to write my thesis about this topic and for the valuable guidance and support throughout this project. I also extend my appreciation to the research group for the insights and valuable discussions during the process.

Finally, I want to thank those who encouraged and supported me through the studies. Special thanks to my family and friends whose significance to the motivation, determination and overall well-being cannot be underlined enough.

Tampere,
Samuli Viinamäki

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Symbols and abbreviations

AEL	Alkaline Electrolyzers
AGC	Automatic Generation Control
BESS	Battery Energy Storage System
C02	Carbon Dioxide
CAPEX	Capital Expenditure
CCfD	Carbon Contracts for Difference
DC	Direct Current
DFC	Direct Frequency Control
DGU	Distributed Generation Units
DHI	Diffuse Horizontal Irradiation
DMPC	Decentralized Model Predictive Control
DoD	Depth of Discharge
EDLC	Electric Double-Layer Capacitor
EMS	Energy Management System
EU	European Union
FEED	Front End Engineering Design
FOAK	First-of-a-kind
FOW	Floating Offshore Wind
FPV	Floating Photovoltaic

GHI	Global Horizontal Irradiation
GW	Gigawatt(s)
H2-ICEs	Hydrogen Internal Combustion Engine
HER	Hydrogen Evolution Reaction
HESS	Hybrid Energy Storage System
HVDC	High-voltage direct current
ITC	Investment Tax Credits
KOH	Potassium Hydroxide
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Analysis
LCIA	Life Cycle Impact Assessment
LCOE	Levelized Cost of Energy
LCOH	Levelized Cost of Hydrogen
MW	Megawatt(s)
NPV	Net Present Value
O&M	operation and maintenance
OER	Oxygen Evolution Reaction
OPEX	Operational Expenditure
PEM	Proton Exchange Membrane
PEMWE	Proton Exchange Membrane Water Electrolysis

POA	Plane of Array Irradiation
PPA	Power Purchase Agreement
PR	Performance Ratio
PTC	Production Tax Credits
PtX	Power-to-X
PV	Photovoltaic
RES	Renewable Energy Sources
RO	Reverse Osmosis
SOEC	Solid Oxide Electrolyser Cells
TEA	Techno-Economic Analysis
WACC	weighted average cost of capital

Declaration of AI use

During the writing process of this Master thesis, Samuli Viinamäki, the author of the thesis, used artificial intelligence (ChatGPT-4.o) to check the spelling, translations, flow, and possible grammatical errors within the text. ChatGPT was only used for proofreading as to assist the author to write the thesis in English, which is not his native language. The author reviewed and edited the contents received from ChatGPT and takes full responsibility for the content of the Master thesis.

1 Introduction

1.1 Background

The transition to a low-carbon energy future has become a global essential step, driven by the urgent need to mitigate climate change and reduce dependence on fossil fuels. Among the solutions being explored, hydrogen stands out as a versatile and sustainable energy carrier with applications spanning from transportation, industry, and energy storage. Hydrogen's potential lies not only in its ability to store renewable energy but also in its capacity to act as a bridge toward a decarbonized energy ecosystem (IEA, 2023; IRENA, 2022).

Offshore hydrogen production, utilizing renewable energy sources (RES) such as wind and solar power, represents a significant advancement in the push for sustainability. Offshore environments offer unused space and energy potential, enabling the development of large-scale hydrogen production facilities (European Commission, 2021). By integrating modular systems and decentralized controls, offshore hydrogen production systems can achieve enhanced reliability, scalability, and flexibility. One of the most significant business cases for green hydrogen production is the concept of an energy island. In these systems, electrolyzers are integrated with offshore wind farms to enable low-cost hydrogen production. By operating off-grid, substantial cost savings are achieved by eliminating the need for an electrical network between the offshore wind farm and the onshore grid.

The offshore environment also introduces unique challenges. Harsh weather conditions, corrosion, and the complexity of infrastructure deployment demand innovative solutions (IRENA, 2022). Additionally, achieving economic viability requires optimizing the integration of RES, electrolyzers, and storage systems while addressing the variability in renewable energy production (IEA, 2023). The intermittency of wind power introduces fluctuations in the electrolyzers input power across various timescales. These variations accelerate the degradation of the electrolyzers stack, shortening its lifespan and reducing overall system reliability. This issue is particularly critical in offshore environments, where maintenance work is expensive. If the rate of change in wind power surpasses the electrolyzers ramp rate, system stability can be compromised. Additionally, the electrolyzers utilization factor can be low, increasing the capital expenditure (CAPEX) per unit of hydrogen produced.

1.2 The Objective and Scope

The primary objective of this thesis is to conduct a comprehensive literature review and case study analysis to assess the feasibility and optimization of offshore hydrogen production systems, more specifically the research aims to:

- **Conduct a literature review** on green hydrogen production systems, energy storage technologies and decentralized control approaches.
- **Perform case study analysis** to identify key factors that affect the feasibility and performance of offshore hydrogen production systems in real-life applications.
- **Assess the technical and economic feasibility** of offshore hydrogen production, with a focus on the integration of RES and hybrid energy storage systems (HESS).

The research aims to contribute to the broader goals of the OptiDCG4H2 project by addressing key challenges in the design, control, and energy management of offshore hydrogen systems. Specially, the study will focus on the integration of RES, in this case offshore wind and solar, with hydrogen production, while also examining the role of HESS.

The thesis consists of two main sections. First there is a literature review section which aims to provide comprehensive understanding of offshore hydrogen production and its different aspects. Literature review takes a look in hydrogen production, markets and supply chain. Then the focus shifts on different ways of producing renewable energy and its storage methods. Most common control methods of offshore hydrogen production applications are discussed to evaluate best available practices. After general overview, economies of offshore hydrogen are considered through techno-economic analysis models. Finally, the literature review briefly discusses the possibilities of digital twins and simulation models.

The second section of the thesis consists of case studies of similar offshore hydrogen projects. Case studies look at four different projects in different stages and examine their key features and challenges, to evaluate the best available techniques. The case study analysis relies on publicly available data from the projects, and other resources. Primary data collection or experimental work will not be included in this thesis. This thesis will not cover onshore hydrogen production or the transportation of hydrogen beyond the scope of offshore systems. While high level cost considerations will be discussed, detailed economic modelling or policy analysis are not included. A visual representation of the logical flow of the thesis can be found in Figure 1.

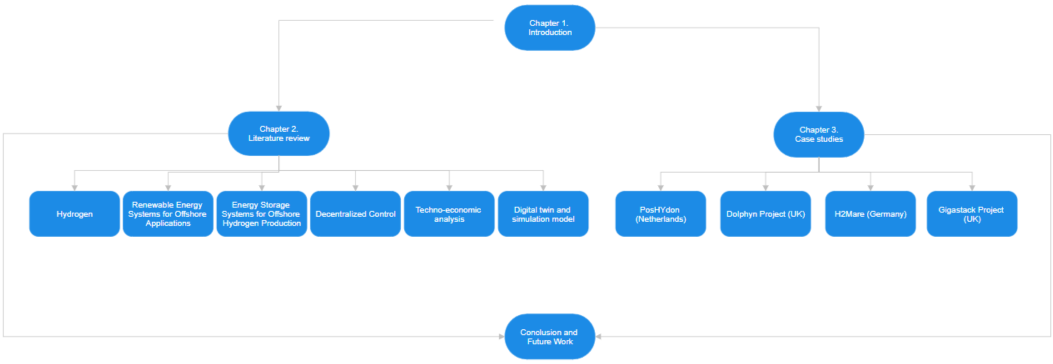


Figure 1. Logical flow of the thesis

2 Literature Review

2.1 Hydrogen

Hydrogen is a versatile energy carrier that has emerged as a vital component in the global transition to a low-carbon economy. Among the various methods of hydrogen production, hydrogen produced with RES, such as wind, solar, or hydroelectric power sources, using water electrolysis, is often referred to as green hydrogen. This production method ensures that there is no direct carbon dioxide (CO_2) emissions during the process. Although green hydrogen is a zero-carbon technology, it is not entirely free from environmental implications. Considering the life-cycle emissions of infrastructure and water usage in the process, which add to the energy and environmental costs through a lifetime evaluation (Incer-Valverde et al., 2023).

In addition to green hydrogen, other methods of hydrogen production are categorized into approximately ten different colours which serve as a simplified way to distinguish between production methods and their environmental impacts. However, this system lacks a universal standard and, because of that, might lead to inconsistencies and confusion in terminology usage (Incer-Valverde et al., 2023). In this thesis, when referring to hydrogen production, it is meant "green hydrogen" unless stated otherwise.

2.1.1 Green Hydrogen Production Methods

Green hydrogen production relies on three primary electrolyser technologies: alkaline electrolyzers (AEL), proton exchange membrane (PEM) electrolyzers, and solid oxide electrolyser cells (SOECs). Each method has its advantages and disadvantages, depending on operational characteristics, efficiency, and costs. A fourth promising method, still in development, is seawater direct electrolysis.

Generally, hydrogen electrolysis is a process where water is electrochemically converted into hydrogen and oxygen. At standard temperature (25 °C) and pressure (1 bar), the

Gibbs free energy change is 237.2 kJ/mol, representing the minimum electrical energy required to initiate the reaction. Additionally, 48.6 kJ/mol corresponds to the thermal energy necessary to account for the total enthalpy change (Abdelsalam et al., 2024), as described in Equation 1:

$$H_2O + 237.2(kJ/mol)_{electricity} + 48.6(kJ/mol)_{heat} \rightarrow H_2 + 0.5\ O_2 \qquad (1)$$

Alkaline electrolyzers are one of the most mature and widely used technologies for green hydrogen production. These electrolyzers operate by splitting water into hydrogen and oxygen using an alkaline solution, typically potassium hydroxide (KOH), as the electrolyte. The process involves two electrodes—anode and cathode—separated by a diaphragm that allows the passage of ions but prevents gas mixing (David et al., 2019).

AELs are known for their relatively low cost and long operational life, making them a popular choice for large-scale hydrogen production. They are particularly effective when paired with RES such as solar photovoltaics (PV) or wind turbines, as they can operate efficiently under variable power inputs. However, their efficiency is generally lower compared to other electrolyser types, and they require regular maintenance to prevent electrolyte degradation (Abdelsalam et al., 2024).

Proton Exchange Membrane Electrolyzers uses a solid polymer electrolyte membrane to conduct protons from anode to cathode, where hydrogen gas is produced. These electrolyzers are characterized by their high efficiency, compact design, and ability to operate at high current densities (Di Caro A, Vitale G, 2024).

PEM electrolyzers are particularly suitable for applications requiring rapid response times and high-purity hydrogen, such as fuel cell vehicles. They are also more compatible with intermittent RES due to their ability to quickly adjust to varying power inputs. However, the high cost of materials, particularly the platinum-based catalysts used in electrodes, remains a significant barrier to widespread adoption. Despite this, PEM electrolyzers are considered a promising technology for medium- to large-scale hydrogen production, especially when paired with renewable energy systems like wind or hydroelectric power (Abdelsalam et al., 2024).

Solid Oxide Electrolysis Cells can be divided into two categories—tubular and flat—depending on geometry, ion type, and electrolyte properties. The two main types are oxygen ion-conducting SOECs (O-SOEC) and proton-conducting SOECs (H-SOEC).

SOECs are high-temperature electrochemical devices operating at temperatures typically between 700℃ and 1000℃ (Xu et al., 2024). These electrolyzers use a ceramic electrolyte to conduct oxygen ions, allowing for highly efficient hydrogen production, especially when waste heat from industrial processes or geothermal energy is available. SOECs are particularly advantageous for their electrical efficiency and ability to produce hydrogen at a lower cost when integrated with thermal energy sources.

However, the high operating temperatures and the need for advanced materials to withstand thermal stress pose significant challenges for widespread use. Despite these challenges, SOECs show significant promise for large-scale hydrogen production, particularly when paired with additional heat sources (Abdelsalam et al., 2024).

Seawater direct electrolysis operates similarly to freshwater electrolysis but in a more complex environment containing various ions, microorganisms, and impurities. The core reactions in seawater electrolysis are the hydrogen evolution reaction (HER) at the cathode and the oxygen evolution reaction (OER) at the anode. However, seawater electrolysis produces chlorine gas and hypochlorous acid, which are corrosive and can damage equipment (Zhao et al., 2025).

The benefits of seawater direct electrolysis include the abundance of seawater, making it a highly suitable resource for hydrogen production, particularly in coastal regions and offshore applications. Additionally, the purity of produced hydrogen is high. However, technology still faces critical challenges before its widespread adoption. One major issue is slow reaction kinetics due to seawater impurities. Corrosion and stability issues also increase maintenance and operation costs, which are already high due to energy consumption and scalability challenges (Zhao et al., 2025). A comparison of different electrolyser types and their characteristics can be found in Table 1.

Table 1. Characteristics of electrolyzers

Characteristic	**Alkaline Electrolyzers**	**Proton Exchange Membrane (PEM) Electrolyzers**	**Solid Oxide Electrolysis Cells (SOECs)**	**Seawater Direct Electrolysis**
Electrolyte	Alkaline solution (KOH or NaOH)	Solid polymer membrane	Ceramic electrolyte	Seawater (natural or modified)
Operating Temperature	60-80°C	50-80°C	>650°C	25-80°C (varies with approach)
Efficiency	65-67%	60-80%	Up to 84%	~50-80% (varies based on conditions)
Current Density	0.2-0.4 A/cm²	0.6-2.0 A/cm²	Not specified	Typically, lower than PEM (~0.1-1.0 A/cm²)
Advantages	- Mature technology - Cost-effective - No precious metals required	- High efficiency - Compact design - Quick response to power fluctuations	- Highest efficiency - Can use waste heat - Potential for syngas production	- No need for freshwater - Abundant seawater resource - Potential for integration with desalination

Disadvantages	- Lower efficiency - Slower response time	- Higher cost - Requires precious metals	- High temperature requirement - Limited large-scale application	- Corrosion and chlorine evolution issues - Complex system design - Lower maturity
Electrode Materials	Nickel-based	Platinum group metals	Not specified	Corrosion-resistant coatings (e.g., mixed metal oxides, titanium-based)
Stack Lifetime (h)	<90,000	<20,000	Not specified	Not well established (current systems <10,000 h)
Maturity	Most mature and widely used	Well-established	Emerging technology	Early-stage development, research ongoing

2.1.2 Hydrogen Supply Chain Consideration

In offshore hydrogen production systems, three primary configurations are considered:

a) **Centralized electrolysis conducted onshore.**
b) **Centralized electrolysis conducted offshore.**
c) **Decentralized electrolysis conducted offshore.**

The economic viability and environmental conditions of each configuration determine the most suitable option. These typologies are evaluated based on key factors such as electrolyser technology selection, floating offshore wind (FOW) platform integration, and energy transmission methods (electric power, offshore hydrogen pipelines, or vessel transportation). Each configuration presents unique advantages and challenges, which must be understood for their applicability in different offshore environments (Ibrahim et al., 2022). Visual representation of different offshore hydrogen configurations can be found in the Figure 2.

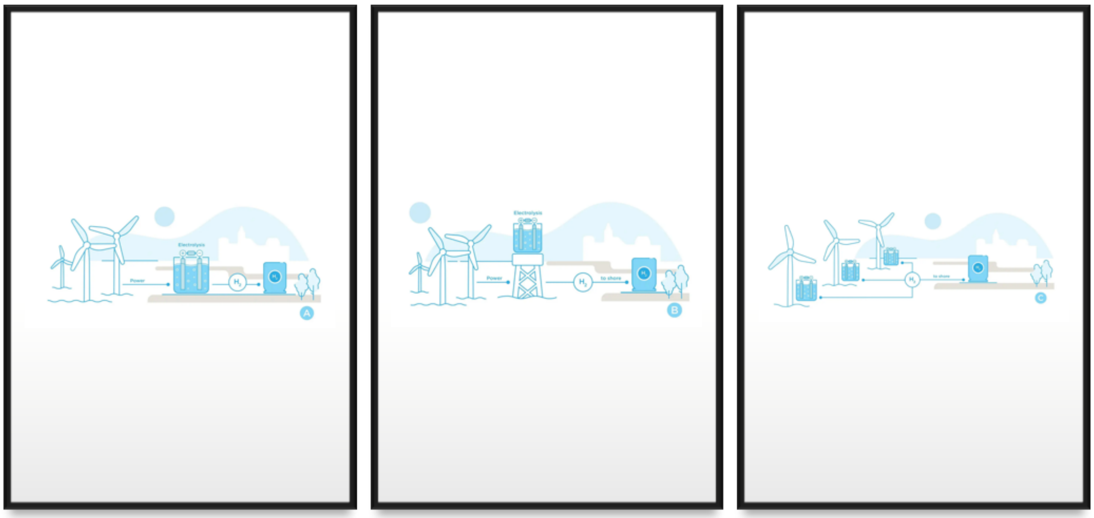


Figure 2. Visual presentation of configurations (Ramboll n.d.)

For centralized onshore electrolysis, AELs are typically used due to their technological maturity and cost-effectiveness. High-voltage direct current (HVDC) submarine cables are used for energy transmission to shore. This configuration is well-suited for near-shore projects but may face limitations in scalability and energy losses over long distances. Additionally, the lack of flexibility for future expansion could pose challenges for large-scale or distant farms (Ibrahim et al., 2022).

The two offshore configurations—decentralized and centralized electrolysis—rely on submarine hydrogen pipelines for energy transmission. This approach is considered more economical for large-scale projects, particularly those farther from shore, as it avoids the capacity constraints of electrical cables, typically limited to ~2GW per cable. Decentralized offshore electrolysis, which utilizes PEM electrolyzers, offers significant advantages in modularity and operational flexibility. PEMs are compact, capable of dynamic operation, and allow for continuous hydrogen production even if individual turbines or electrolyzers are offline. Their modular design also facilitates easier expansion (Ibrahim et al., 2022).

Centralized offshore electrolysis can use either PEM or AEL technologies, depending on site-specific analyses. This configuration simplifies maintenance for individual turbines and may benefit from economies of scale, particularly with advancements in large-scale electrolyzers. However, a major drawback is the risk of a complete production shutdown in the event of system failure. The need for a dedicated floating vessel to house the electrolysis facility also adds to CAPEX (Ibrahim et al., 2022).

2.1.3 Hydrogen Storage Consideration

Hydrogen storage is a critical challenge in the development of a sustainable hydrogen economy. While hydrogen has a high energy content per unit mass, 120 MJ/kg, its low volumetric energy density poses difficulties for efficient storage. Various methods have been developed to address this issue, each with its own set of advantages and disadvantages (Usman, M. R. 2022). This chapter provides an overview of the primary hydrogen storage methods, including compressed hydrogen, liquefied hydrogen, cryo-compressed hydrogen, metal hydrides, complex metal hydrides, physical adsorption, and liquid organic hydrogen carriers (LOHCs). Compiled description of different storage methods can be found in Table 2.

Table 2. Qualities of hydrogen storage methods

Storage Method	Description	Advantages	Disadvantages
Compressed Hydrogen	Stored in high-pressure tanks up to 10,000 psi	High energy density, easy transportation, relatively safe	Requires high-pressure storage, energy-intensive compression
Liquefied Hydrogen	Cryogenically cooled to -253°C	Ease of storage and transportation	Energy-intensive cooling process, boil-off losses

Cryo-Compressed Hydrogen	Combines cryogenic cooling and high-pressure compression	Higher volumetric energy density, reduced boil-off losses	Complex system, high cost, energy consumption
Metal Hydrides	Hydrogen chemically bonded to metals	High storage density, low pressure storage, improved safety	Heavy storage units, expensive materials
Complex Metal Hydrides	Hydrogen stored in complex anions with ionic bonding	High volumetric and gravimetric hydrogen densities	Poor thermodynamic and kinetic properties
Physical Adsorption	Hydrogen absorbed onto porous materials	Fast, reversible storage at ambient and cryogenic conditions	Requires optimized adsorbent materials
Liquid Organic Hydrogen Carriers (LOHCs)	Organic compounds that absorb and release hydrogen	Efficient storage and transportation	Energy-intensive dehydrogenation process

2.1.3.1 Compressed Hydrogen

Compressed hydrogen is one of the most widely used storage methods due to its maturity and simplicity. It involves storing hydrogen gas at high pressures, typically up to 700 bars. The primary advantage of this method is its high filling and quick release rates, making it suitable for applications requiring quick refuelling. Additionally, the technology for compressing hydrogen is well-developed and widely available. Another benefit is that no additional energy is required for hydrogen release, which simplifies the storage system (Usman, M. R. 2022).

Despite its advantages, compressed hydrogen storage has economic and practical challenges. Compressing hydrogen to high pressures consumes significant amount of energy, approximately 13–18% of the lower heating value of hydrogen, reducing overall efficiency. Safety is another concern, as high-pressure storage poses risks of explosions due to sudden shocks (Usman, M. R. 2022).

2.1.3.2 Liquefied Hydrogen

Storing hydrogen in its liquid state increases its volumetric energy density (71 g/l) which is significantly higher than in compressed hydrogen. Liquefied hydrogen storage involves cooling hydrogen to cryogenic temperatures to achieve a liquid state. This method is particularly advantageous for applications requiring compact storage systems. Additionally, the low adiabatic expansion energy at cryogenic conditions helps avoid damage during sudden leaks, enhancing safety (Usman, M. R. 2022).

Despite its advantages, the energy cost of liquefaction is substantial, consuming 30–40% of hydrogen's heating value. Boil-off losses—ranging from 1.5–3% of stored hydrogen per day—pose practical challenges, particularly for long-term storage, leading to substantial losses over time. The need for specialized cryogenic storage and handling infrastructure further complicates the adoption of this method and increases its costs (Usman, M. R. 2022).

2.1.3.3 Cryo-Compressed Hydrogen

Cryo-compressed hydrogen combines the benefits of compressed and liquefied hydrogen by storing hydrogen at cryogenic temperatures and high pressures (250-350 bar), achieving even higher densities (80 g/L) with reduced boil-off losses. This approach provides improved dormancy periods, enabling storage without significant hydrogen losses for several days (Usman, M. R. 2022).

Cryo-compressed hydrogen storage also has its limitations. The need for expensive double-walled technologies increases overall system costs. Maintaining cryogenic temperatures and high pressures requires significant energy input, impacting overall efficiency and economics. Despite these challenges, cryo-compressed hydrogen storage shows promise for certain applications, particularly where high energy density and rapid refuelling are critical. Challenges related to infrastructure development, like compressed and liquefied hydrogen, remain significant barriers to widespread adoption (Brunner, T., Kircher, O. 2016).

2.1.3.4 Metal Hydrides and Complex Hydrides

Metal hydrides store hydrogen chemically by forming hydride bonds with metal alloys. These materials offer high volumetric energy densities, moderate operating conditions, and safer storage options compared to gaseous or liquid hydrogen. For example, magnesium hydride (MgH_2) provides a volumetric density twice that of liquid hydrogen (Züttel, A. 2004).

However, metal hydrides face limitations in terms of kinetics and thermodynamics. High desorption temperatures, typically exceeding 300°C, and slow hydrogen release rates hinder practical applications. Efforts to improve these properties include nano structuring, alloying, and catalysis. For instance, adding Nb_2O_5 as a catalyst has demonstrated significant enhancements in hydrogen release rates (Usman, M. R. 2022).

Complex metal hydrides, such as alanates and borohydrides, offer high hydrogen storage capacities. These hydrides store hydrogen through covalent bonding of hydrogen atoms to a central atom in a coordination complex. Sodium alanate ($NaAlH_4$) has reversible hydrogen storage capacities of up to 5.6 wt%, while borohydrides like lithium borohydride ($LiBH_4$) offer hydrogen contents reaching 18.5 wt% (Usman, M. R. 2022).

Despite their potential, complex metal hydrides have several challenges. Alanates require high operating temperatures and pressures for rehydrogenation, while borohydrides often produce undesirable byproducts during hydrogen release, which can contaminate the hydrogen supply and damage fuel cell systems (Züttel, A. 2004).

2.1.3.5 Physically Adsorbed Hydrogen

Physical adsorption involves storing hydrogen on the surface of solid materials through van der Waals interactions. Porous materials such as activated carbon, zeolites, and metal-organic frameworks are used due to their rapid adsorption/desorption kinetics and low enthalpy changes, making thermal management straightforward. MOFs, for example, offer high surface areas, with capacities reaching 7.9 wt% under cryogenic conditions. This method offers reversible storage and low enthalpy of adsorption, simplifying heat management (Usman, M. R. 2022).

However, the practicality of physical adsorption is constrained by low room-temperature storage capacities, necessitating cryogenic temperatures or high pressures. Additionally, losses can occur at cryogenic temperatures, like boil-off losses in liquid hydrogen storage. Consequently, physically adsorbed hydrogen storage is not considered a viable option for large-scale applications (Samantary, S. et al., 2021).

2.1.3.6 Liquid Organic Hydrogen Carriers (LOHCs)

Liquid organic hydrogen carriers (LOHCs) store hydrogen chemically by reacting with hydrogen-deficient organic molecules, such as methylcyclohexane, toluene, and dibenzyltoluene. These carriers offer advantages such as the use of existing infrastructure for liquid fuels and high hydrogen capacities ranging from 1.7 to 7.3 wt%, e.g., 6.2 wt% for methylcyclohexane (Usman, M. R. 2022).

Challenges with LOHCs include high dehydrogenation temperatures and the energy-intensive nature of the hydrogenation/dehydrogenation cycle, which limits overall efficiency. Some LOHCs are prone to catalyst deactivation, reducing efficiency over time (Züttel, A. 2004).

2.1.4 Global Trends in Hydrogen Production

Hydrogen is increasingly recognized as a key component in the global transition to a low-carbon economy. Its potential to decarbonize various sectors, including transportation, industry and energy storage, has led to significant interest and investments towards hydrogen production, which has led to advancements in hydrogen production technologies.

The global demand for hydrogen has been steadily increasing, driven by its applications for refining, ammonia production and emerging use in transportation and power generation. According to the International Energy Agency, global hydrogen demand reached 94 million tons (Mt) in 2021, with most of it being used in industrial processes (IEA, 2021). The IEA projects that hydrogen demand could grow to 130 Mt by 2030, with a significant portion coming from new applications such as fuel cell vehicles and power generation (IEA, 2021).

Particularly the production of low emission green hydrogen is expected to grow and IEA estimates that its share of production could reach 38 Mt by 2030, based on announced projects (IEA, 2024.). The growth is supported by government policies, corporate initiatives, and technological advancements which have a crucial role during the adoption of green hydrogen. Examples of these policies are found all over the world, for example in the European Union (EU) The European Green Deal includes ambitious targets for hydrogen production, aiming to install at least 40 GW of electrolyzers by 2030 (IEA, 2024). In the United States the Inflation Reduction Act provides significant incentives for green hydrogen production, including tax credits for low-carbon hydrogen (IEA, 2024). In Middle East, countries like Saudi Arabia, are investing in green hydrogen projects, aiming to become global leaders in hydrogen export (IEA, 2024). Australia is developing large-scale green hydrogen hubs, leveraging its abundant renewable energy resources (IEA, 2024).

2.1.5 Hydrogen Markets

The EU has set a strategic goal to consume 20 million tonnes of renewable hydrogen by 2030. However, current consumption stands at just 7.2 Mt, with 98.7% of this hydrogen still produced from fossil fuels (ACER, 2024). This indicates a significant gap between the EU's renewable hydrogen targets and the current market reality, highlighting the challenges in transitioning from fossil-based to renewable hydrogen production.

The current installed capacity of electrolysers in Europe is just over 200 MW, with an additional 1.8 GW worth of projects under construction and scheduled to be operational by the end of 2026. (ACER, 2024). However, the EU missed its intermediate target of 6 GW of electrolyser capacity by 2024, as well it seems likely that it will miss the more ambitious target of 100+ GW needed to meet the 2030 renewable hydrogen production goal of 10 Mt. This shortfall is attributed to uncertainties in demand, high production costs, and the slow uptake of renewable hydrogen in industrial and transport sectors.

National strategies across EU member states vary in ambition and alignment with EU-wide targets. While some countries, such as Germany and Spain, have set ambitious goals for electrolyser capacity and renewable hydrogen production, others lag, leading to uneven sector development. This disparity in national ambitions is reflected in the pace of regulatory developments, with only a few member states, such as Denmark and Germany, having introduced specific regulatory provisions for hydrogen network planning and access tariffs (ACER, 2024).

Infrastructure development is another critical factor in the hydrogen market's evolution. The EU has ambitious plans for hydrogen infrastructure, including a proposed 42,000 km hydrogen network by 2034, along with plans for import capacity and storage expansion. However, several challenges must be addressed, including the repurposing of existing gas networks, which could reduce costs but requires careful regulatory oversight to address technical and economic considerations. Additionally, integrating hydrogen and electricity networks is crucial, as achieving the EU's target of 10 Mt of renewable hydrogen production will require substantial investments in electricity networks to connect renewable energy plants and electrolysers (ACER, 2024).

The European hydrogen market is still in an emerging phase, characterized by localized production and consumption networks primarily supported by bilateral agreements. Hydrogen transport and storage infrastructure remains limited, and the market lacks the liquidity and transparency seen in more mature commodity markets, such as natural gas. The absence of a unified market structure and standardized regulations poses significant challenges for producers, consumers, and infrastructure providers. The European Green Deal envisions a transition from these isolated hydrogen hubs to a more interconnected European hydrogen economy. Key policy measures proposed to accelerate market development include direct financial subsidies for hydrogen production infrastructure, carbon contracts for difference (CCfD) to bridge the cost gap between hydrogen and fossil fuels, and hydrogen usage quotas for specific industrial applications. Additionally, a gradual increase in CO_2 pricing is expected to enhance hydrogen's economic viability relative to carbon-intensive alternatives (European Commission, 2020).

Developing a hydrogen commodity market requires addressing several key areas, including market design, infrastructure regulation, and policy support. One of the primary challenges in establishing a European hydrogen market is the absence of a standardized and scalable trading mechanism. The natural gas market is often cited as an analogy for hydrogen market development due to its similar infrastructural and regulatory requirements. Essential regulatory measures include third-party access (TPA) to hydrogen infrastructure, unbundling of hydrogen production from transportation, and the implementation of an entry-exit system for hydrogen transmission. However, transitioning from a bilateral-contract-based market to a liquid commodity trading system requires additional market design elements, including transparent pricing mechanisms and certification systems (European Commission, 2020).

Policy measures are crucial for supporting the hydrogen market's development, particularly in its early stages. The EU has proposed various instruments, including direct industry subsidies, CCfD, and adjustments to green electricity taxation (Steinbach & Bunk, 2024). These measures aim to close the cost gap between green hydrogen and fossil fuels, making hydrogen more competitive. Additionally, the introduction of hydrogen usage quotas for specific applications, such as green steel production, could create demand-side incentives for hydrogen adoption.

Hydrogen certification plays a crucial role in ensuring market transparency and facilitating cross-border trade. Current certification schemes remain inadequate for large-scale international transactions, leading to calls for an EU-wide system based on Guarantees of Origin. While the mass balance approach has been suggested to ensure accurate greenhouse gas emissions tracking, many stakeholders favour a book-and-claim system, which allows for greater flexibility and more efficient commodity trading. Implementing such a certification scheme is pivotal to fostering trust among market participants and enabling the establishment of a functional hydrogen trading ecosystem.

One of the key challenges in the current regulatory landscape is the uncertainty surrounding hydrogen certification and the strict requirements for green hydrogen production. The delegated act of the Renewable Energy Directive II (RED II) mandates that green hydrogen must be produced using renewable electricity that is geographically and temporally correlated with hydrogen production. Additionally, starting in 2026, only electricity from newly built renewable energy sources can be used (Steinbach & Bunk, 2024). While these requirements are intended to ensure the sustainability of hydrogen production, they may also hinder market development by increasing costs and delaying project timelines.

In terms of market structure, the future hydrogen market is expected to evolve through several phases. During the initial phase, until around 2025, the focus will be on scaling up hydrogen production and demonstrating its viability in decarbonizing existing industries (Steinbach & Bunk, 2024). During this period, localized hydrogen "islands" are expected to emerge, with production and consumption occurring within isolated networks. The second phase, 2025-2030 envisions greater integration of hydrogen into the broader energy system, including the development of a hydrogen pipeline network and the establishment of EU-wide standards for transportation and cross-border trade. By 2030, the market is expected to become more liquid, with prices driven by global supply and demand.

2.1.5.1 Role of Renewable Hydrogen Production in hydrogen market

Renewable hydrogen is central to the EU's efforts to reduce greenhouse gas emissions and achieve climate neutrality by 2050. The EU's REPowerEU plan, introduced in response to the energy crisis triggered by the Russian invasion of Ukraine, has further emphasized the importance of renewable hydrogen.

The plan sets a strategic goal of 20 Mt of renewable hydrogen consumption by 2030, with half of this amount to be produced domestically and the remainder imported. This ambitious target underscores the EU's commitment to scaling up renewable hydrogen production as part of its broader energy security and decarbonization agenda (ACER, 2024).

2.1.5.2 Challenges of Renewable Hydrogen in the Market

The cost of producing renewable hydrogen via electrolysis remains substantially higher than that of hydrogen produced from fossil fuels. According to the ACER report, renewable hydrogen is currently three to four times more expensive than fossil-based hydrogen, primarily due to the high CAPEX associated with electrolysers and the cost of renewable electricity (ACER, 2024). The EU's Renewable Fuels of Non-Biological Origin (RFNBO) production rules, which mandate strict criteria for renewable hydrogen to qualify as sustainable, further increase production costs. These rules require that the electricity used for electrolysis meets additionality, temporal correlation, and geographical correlation criteria, adding complexity and cost to renewable hydrogen projects (ACER, 2024).

The current installed capacity of electrolysers in Europe is just over 200 MW, far below the 6 GW target set for 2024 and the 100+ GW needed to meet the 2030 production target of 10 Mt of renewable hydrogen (ACER, 2024). While projects accounting for an additional 1.8 GW is under construction, most planned projects, around 60 GW, are still awaiting final investment decisions. This delay is largely due to uncertainties in future hydrogen demand, high production costs, and the availability of funding. The slow deployment of electrolysers is a significant bottleneck in scaling up renewable hydrogen production.

The development of hydrogen infrastructure, including pipelines, storage facilities, and import terminals, is critical for the growth of the renewable hydrogen market. However, current infrastructure plans are largely based on aspirational demand projections rather than concrete market needs, increasing the risk of overinvestment and underutilization (ACER, 2024). Repurposing existing natural gas infrastructure for hydrogen transport could reduce costs, but this approach presents technical and economic challenges, including the need for significant modifications to pipelines and compressors to handle hydrogen's unique properties (ACER, 2024).

Renewable hydrogen production is heavily dependent on the availability of renewable electricity. The EU's target of 10 Mt of renewable hydrogen production by 2030 will require approximately 550 TWh of renewable electricity, equivalent to more than three-quarters of the electricity currently produced by wind and solar in the EU (ACER, 2024). This massive demand for renewable electricity poses challenges for grid development, as significant investments are needed to connect new renewable energy plants and electrolysers to the grid. Additionally, the integration of electrolysers into the electricity system must be carefully managed to avoid exacerbating grid congestion and increasing the cost of remedial actions (ACER, 2024).

The regulatory framework for renewable hydrogen is still evolving, with many EU member states yet to transpose the hydrogen and decarbonised gas market directive into national legislation. This lack of regulatory clarity creates uncertainty for investors and project developers, delaying the deployment of renewable hydrogen projects. Furthermore, the role of low-carbon hydrogen, produced from natural gas with carbon capture and storage, remains debated. While low-carbon hydrogen could help bridge the cost gap and accelerate market development, it risks creating long-term lock-in effects that could hinder the transition to fully renewable hydrogen (ACER, 2024).

The high capital costs and long payback periods associated with renewable hydrogen projects make them particularly vulnerable to financing challenges. Although EU funding mechanisms, such as the European Hydrogen Bank and the Innovation Fund, provide support for renewable hydrogen projects, navigating the complex landscape of funding schemes can be difficult for investors. Additionally, the lack of a liquid market for hydrogen and the absence of long-term offtake agreements increases the financial risks for project developers, further slowing market development (ACER, 2024).

2.2 Renewable Energy Systems for Offshore Applications

Advancements in research and development (R&D), supportive government policies, and significant cost reductions have driven the exponential growth of wind energy production since the turn of the century. According to the International Energy Agency, global installed wind generation capacity—both onshore and offshore—has increased by a factor of 98 over two decades, from 7.5 GW in 1997 to 733 GW in 2018, and continues to grow. Over the past decade, offshore wind energy production has grown proportionally more than onshore, and this trend is expected to continue (International Renewable Energy Agency, n.d.).

2.2.1 Technological Advances in Offshore Wind Energy

Technological advancements have played a crucial role in the development of wind energy production. Early wind turbines in the 1980s were relatively small, with typical turbines in 1985 having a rated capacity of 0.05 MW and a rotor diameter of 15 meters. Over time, turbine capacity has increased significantly. By 2020, new wind power projects featured turbines with capacities of 3–4 MW for onshore installations and 8–12 MW for offshore installations (International Renewable Energy Agency, n.d.).

One of the most notable advancements in offshore wind technology is the development of larger and more powerful turbines. Larger turbines benefit from economies of scale, as they can capture more energy from the wind and reduce the number of turbines needed for a given capacity. This is particularly important for offshore projects, where installation and maintenance costs are significantly higher than onshore (Markard & Petersen, 2009).

2.2.1.1 Factors Affecting Wind Energy Production Potential

In addition to increased size, offshore turbines have been designed to withstand the harsh conditions of marine environments. Stronger and steadier winds, saltwater corrosion, waves, and extreme weather events pose significant challenges for offshore wind farms. To address these issues, turbine manufacturers have developed more robust and reliable designs. Advanced materials and coatings are used to resist corrosion, while improved mechanical and electrical components reduce failure risks and maintenance needs, enhancing the overall efficiency and durability of offshore turbines (Markard & Petersen, 2009).

Despite regulatory advancements, offshore wind projects must navigate complex environmental and licensing challenges. These processes can be time-consuming and require coordination with multiple stakeholders, including regulatory authorities, environmental organizations, and local communities. However, technological advancements have helped mitigate some environmental impacts of offshore wind farms (Markard & Petersen, 2009).

Offshore wind farms offer several advantages over onshore installations. They benefit from stronger and more consistent wind speeds, as the wind over the sea is less affected by obstacles such as buildings, trees, and terrain. Consequently, offshore wind turbines have greater production potential (Hietala, 2020). Additionally, offshore wind farms have a lower visual and noise impact on human populations, as they are located far from residential areas. This reduces public opposition and enables the installation of larger turbines. Offshore wind farms can also be located closer to major coastal cities, reducing the need for long-distance transmission lines and associated energy losses (Hietala, 2020).

2.2.1.2 Analytical Approach to Wind Energy Potential

Wind energy production potential depends on several factors. To estimate the potential power output of wind farms, it is critical to understand the influencing factors and key variables. Through these factors a primary equation for wind farms power output potential is

$$P = \frac{1}{2} * \rho * \pi * r^2 * v^3 * \eta_1 * \eta_2 \tag{2}$$

Where ρ is air density, r is rotor size, v is wind speed, $\eta_1 \; and \; \eta_2$ are system efficiencies.

The equation considers several key factors: wind speed, air density, the swept area of the turbine blades, and the efficiency of the turbine itself. By isolating and analysing these factors, the suitability of a site can be evaluated, and appropriate turbine designs can be assessed. This process helps maximize energy capture and predict energy production under varying conditions.

Wind speed is the most critical factor in wind power generation, with a cubic relationship to power output. Even slight increases in wind speed significantly boost energy production, emphasizing the need for locations with consistently strong winds. Air density, affected by altitude and temperature, also impacts energy potential, as denser air carries more kinetic energy. The swept area of the turbine blades is equally vital, with larger blades capturing more wind, though structural and logistical constraints must be considered. Advances in rotor design and generator efficiency further enhance turbine performance across varying wind conditions. However, this equation offers a simplified approach and does not account for all possible variables (Dahmouni et al., 2011). Table 3. Contains the compiled information of effecting factors and their impact on production potential.

Table 3. Effecting factors of wind energy production

Factor	**Category**	**Impact on Production Potential**
Wind Speed	Environmental	Cubic relationship with power output (doubling wind speed increases power 8×); most critical factor
Air Density	Environmental	Higher density (lower altitude/colder temps) increases kinetic energy capture
Rotor Diameter	Technical (Turbine Design)	Larger swept areas capture more wind energy; scales quadratically with radius
Power Coefficient (Cp)	Technical (Efficiency)	Maximizes energy extraction (theoretical limit: 59.3% per Betz's Law)
Hub Height	Technical (Turbine Design)	Taller towers access stronger, steadier winds at higher altitudes
Turbulence	Environmental	Reduces turbine efficiency and increases mechanical wear
Wake Loss Effect	Technical (Site Layout)	Downstream turbines lose 5–20% output due to upstream turbine interference

Surface Roughness	Environmental	Rough terrain (e.g., forests) reduces wind speed near ground, in offshore applications not an affecting factor
Temperature	Environmental	Affects air density and material expansion/contraction in turbine components
Grid Availability	Operational	Limits energy delivery if transmission infrastructure is inadequate
Maintenance Practices	Operational	Downtime and component reliability directly affect annual energy production
Wind Shear Coefficient	Environmental	Vertical wind speed gradient influences optimal hub height selection

2.2.2 Economic Approach to Wind Energy Production

The economics of wind energy production are influenced by capital costs, variable costs and wind resource availability. Understanding these variables is essential for assessing the competitiveness of wind energy compared to other electricity-generating technologies.

2.2.2.1 Capital Costs

Capital costs represent the most significant component of wind energy production, accounting for up to 80% of the total lifetime costs. These include expenses related to turbines, grid connections, civil works, and initial investments such as development, engineering, licensing, and permits (Blanco, 2009). For offshore wind projects, capital costs range from $1,462 to $7,000 per kilowatt (kW), with an average of $3,354 per kW for European projects built between 2001 and 2007. These costs include turbine procurement, foundation construction, electrical interconnection, and installation (Snyder & Kaiser, 2009).

The wind turbine itself is the largest single cost component, compromising the production, blades, transformers, transportation, and installation. The cost of the turbine can vary significantly depending on the model, market, and location. For offshore wind farms, installation and foundation costs constitute a substantial portion of the overall capital investment. Installation expenses alone can account for about 20% of total capital costs, while foundation construction represents an additional 20%. These high costs are attributed to the complexities of offshore construction, including marine logistics, deeper water depths, and harsher environmental conditions (Snyder B, Kaiser M 2009).

Grid connection costs include the expenses for cables, substations, and power evacuation systems. These costs have been increasing, particularly as more wind farms are connected to the transmission network rather than the distribution grid. Civil works, such as foundations and road construction, also contribute to capital costs, with variations depending on the site’s accessibility and geotechnical conditions (Blanco, 2009). When considering offshore wind farms the costs in this section are significantly larger compared to onshore.

2.2.2.2 Variable Costs

Variable costs, which include operation and maintenance (O&M) expenses, land rental, insurance, taxes, and managements, account for approximately 20% of the total investment in a wind energy project. These costs are relatively low compared to fossil fuel-based electricity generation but are subject to significant variations depending on the location and age of the turbines.

O&M costs represent the most significant portion of variable costs, covering repairs, spare parts, and routine maintenance. While the annual downtime of wind turbines is typically less than 2%, O&M costs can vary considerably based on the turbine's age and size. For example, newer and larger turbines generally have lower O&M requirements compared to older, smaller models (Blanco, 2009).

Other variable costs include land and sub-station rental, insurance, taxes, and management activities. These costs are less predictable and can vary significantly between countries and regions. For instance, in Germany, O&M costs for wind turbine installed between 1997 and 2001 were found to be around 0.3-0.4 € cent/kWh in the first two years, increasing to 0.6-0.7 €cent/kWh after six years (Blanco, 2009).

2.2.2.3 The Role of Wind Resources

The local wind resource is the most critical factor affecting the profitability of wind energy investments. The capacity factor, which expresses the percentage of time a wind farm produces electricity during a representative period, is heavily influenced by the wind resource. For onshore installations, the average number of full-load hours ranges from 1,700 to 3,000 hours per year, depending on the location (Blanco, 2009). Offshore installations run up to 4500 full load hours per year, more than double that of onshore turbines (Klinger and Müller, 2017b).

The correct micro-location of each wind turbine is crucial for maximizing energy production. Factors such as array losses, blade soiling, electrical losses, and downtime for maintenance can reduce net generation by 10–15% compared to theoretical energy generation based on wind power curves (Blanco, 2009).

2.2.2.4 The Cost Equation for Wind Energy Production

The generation cost of wind energy can be calculated using following equation:

$$Generation\ cost(€/kWh) = \frac{Capital\ costs\ (€) + Variable\ costs\ (€)}{Total\ electricity\ produced\ (kWh)} \qquad (3)$$

where:

- **Capital costs** include the cost of the wind turbine, grid connection, civil works, and other initial investments and investments costs, such as interests.

- **Variable costs** include O&M, land rental, insurance, taxes, and management.
- **Total electricity produced** depends on the capacity factor, which is influenced by the wind resource, turbine specifications, and site characteristics.

For example, the generation cost of an onshore wind farm with a capital cost of 1250 €/kW, O&M costs of 1.2 €cent/kWh, and a capacity factor of 23% (2100 full load hours) is estimated to be between 4.5 and 8.7 €cent/kWh (Blanco, 2009).

The long-term cost trends of wind energy are influenced by technological advancements, economies of scale, and policy measures. Learning curves, which analyse cost reductions as a function of cumulative production, suggest that wind energy costs could decrease by 9-17% each time the total installed capacity doubles (Blanco, 2009).

Policy measures can play a significant role in reducing the generation costs of wind energy. These include R&D in new materials, improved O&M techniques, advanced sitting and forecasting methods, and long-term legal stability. Policies that reduce the risk premium and provide access to cheaper financing can further lower the overall cost of wind energy projects (Blanco, 2009).

2.2.3 Potential of Floating Photovoltaic Systems

Floating Photovoltaic (FPV) systems involve the installation of solar panels on floating structures that are anchored to the bed of water bodies such as lakes, reservoirs, and offshore marine environments. This approach addresses the issue of land scarcity and offers several other additional benefits. FPV systems can reduce water evaporation due to the shading effect of solar panels, and they can be integrated with other industries such as aquaculture, creating synergistic relationships. Moreover, the cooling effect of water can enhance efficiency of PV modules, leading to higher energy efficiency compared to traditional land-based systems. (Wang & Lund, 2022).

The potential of FPV systems extends beyond inland water bodies to offshore environments, where the vast expanse of open water offers new opportunities for larger-scale energy generation. Offshore FPV systems present a promising avenue for further expansion of solar energy, especially in regions with high population densities near coastlines. According to Wang and Lund (2022), approximately 50% of the world's population resides within 100 kilometres of the coast, making offshore FPV systems a viable solution for meeting the energy needs of these densely populated areas.

2.2.3.1 Technical Feasibility

FPV systems present a compelling alternative to traditional land-based solar installations, leveraging unique advantages provided by their aquatic environment. One of the primary benefits of FPV systems is the natural cooling effect of water bodies. Solar panels typically operate less efficiently as their temperature rises, but water-based installations benefit from thermal regulation. Studies indicate that FPV systems can achieve up to 11% higher efficiency than ground-mounted systems due to reduced thermal losses (Sahin et al., 2020). This cooling effect is particularly advantageous in regions with high solar irradiation and ambient temperatures, helping FPV systems maintain optimal performance.

The integration of bifacial solar panels further enhances FPV system efficiency. Unlike traditional monofacial panels, bifacial panels capture reflected solar radiation from the water surface, which acts as a highly effective reflector. This dual-sided energy capture significantly boosts overall power output, presenting a promising opportunity to maximize energy generation. Additionally, FPV systems can incorporate innovative cooling and cleaning technologies to enhance the performance. Water-based cooling systems, floating tracking cooling concentrator systems, and phase-change material (PCM)-based cooling methods can increase power efficiency by up to 26%, depending on the technology used (Nizetić et al., 2016; Hadipour et al., 2021). Automated cleaning systems can also help mitigate soiling losses, a common issue that reduces solar panel efficiency. By integrating these solutions, FPV installations can achieve higher energy yields and longer operational lifespans (Kumar et al., 2023).

The development of floating FPV systems for offshore environments has required innovative solutions to ensure durability and efficiency under harsh marine conditions. A significant advancement in this domain is the use of ocean-grade aluminium platforms, which provide a service life exceeding 30 years. This improvement enhances the long-term viability and sustainability of offshore FPV installations, making them a practical choice for renewable energy generation in challenging environments (Srinivasan, Soori, & Ghaith, 2024).

Structural integrity is a critical focus for offshore FPV systems, as they must withstand dynamic marine conditions such as wave and wind load while resisting the corrosive effects of seawater. Innovative platform designs like the Heliofloat Solar Platform and the Solarduck Floating Solar Platform have been developed to address these challenges. The Heliofloat platform employs lightweight, flexible cylindrical materials that effectively dampen wave energy, ensuring stability and durability. In contrast, the Solarduck platform features a rigid triangular structure constructed from lightweight materials, which leverages multidirectional waves for self-balancing. These advancements demonstrate the growing potential of offshore FPV systems to operate efficiently and reliably in demanding marine environments (Srinivasan et al., 2024).

One of the potential advantages of FPV is the possibility to integrate it with other infrastructures, such as offshore wind farms. The complementary nature of solar and wind energy ensures a more consistent and reliable energy output, balancing the variability of each source. Moreover, FPV systems can leverage the existing infrastructure of wind farms, including grid connections, substations, and maintenance facilities, significantly reducing capital and operational costs. This synergy has the potential to lower expenses and minimize the environmental impact by avoiding additional seabed disturbances.

Despite its advantages, integrating FPV systems with offshore wind farms presents several challenges. Structurally, FPV platforms must coexist with wind turbines and withstand harsh marine conditions, including waves, tides, and storms. Efficient electrical integration is another hurdle, requiring advanced grid management to handle the combined energy output. The high initial investment for hybrid systems and the complexity of maintenance in remote offshore environments add to the difficulty. Regulatory frameworks may also need to evolve to accommodate these hybrid installations, addressing permitting and operational standards tailored to combined renewable energy systems. (Kumar et al., 2023).

2.2.3.2 The Role of Radiation Resources

The technical feasibility of a PV power plant is fundamentally dependent on solar irradiation, which serves as the primary energy input. Solar irradiation, typically measured in watts per square meter (W/m²), consists of Global Horizontal Irradiation (GHI) and Plane of Array Irradiation (POA). GHI represents the total solar radiation incident on a horizontal surface and is mathematically expressed as:

$$GHI = DHI + G_n cos(\theta_z) \tag{4}$$

where *DHI* represents Diffuse Horizontal Irradiation (scattered radiation), G_n is Direct Normal irradiation (direct sunlight) and (θ_z) is the solar zenith angle. POA, the radiation received by PV modules (G_t), is derived from GHI using transposition factors, e.g., Hay, Perez and is calculated as:

$$G_t = GHI \times Transposition\ factor \tag{5}$$

Not all received irradiation is effectively converted into usable energy due to various losses, which can be classified into optical, array, and system losses. Optical losses arise from factors such as near and far shading, Incidence Angle Modifier (IAM) shading, and soiling (Marion et al., 2005). Array losses result from suboptimal irradiation conditions, temperature effects, module quality degradation, mismatch losses, and wiring inefficiencies (King et al., 2004). System losses are associated with inefficiencies in inverters and medium-to-high voltage transmission (González-Longatt, 2005).

The performance of a PV system is often evaluated using the Performance Ratio (PR), defined as the ratio of actual energy output to the reference yield. A well-optimized PV system typically exhibits a PR of at least 80% (IEC 61724, 1998). Reference yield (E) is calculated as:

$$E = G_t \times A \times \eta \tag{6}$$

where $G_t$is POA radiation, A is area and η is module efficiency

Actual energy output, accounting for PR degradation over time, is as:

$$\text{Actual Energy Output} = \frac{Performance\ Ratio \times DC\ Capacity \times POA\ Irradiance}{Reference\ Irradiance(1000W/m^2)} \tag{7}$$

This approach ensures accurate energy yield estimation while considering system losses and degradation.

2.2.3.3 Economic Feasibility

The Levelized Cost of Electricity (LCOE) for offshore floating FPV systems is generally higher than that of onshore installations due to additional costs associated with corrosion-resistant materials, mooring systems, and installation in harsh marine environments. However, offshore FPV systems can still be competitive in specific contexts (Golroodbari et al., 2021). For instance, a study conducted on an offshore oil and gas platform demonstrated that an FPV system could achieve an LCOE of $261 USD/MWh, with a discounted payback period of 9.5 years (Srinivasan et al., 2024). This indicates that, despite higher initial costs, offshore FPV systems can be economically viable, particularly in locations where land availability is limited or where synergies with existing offshore infrastructure can be leveraged (Golroodbari et al., 2021).

Net Present Value (NPV) calculations further support the economic feasibility of offshore FPV systems. The NPV of offshore FPV projects can be positive, especially when subsidies or favourable policy measures are in place. For example, Golroodbari et al. (2021) found that the integration of offshore FPV systems within existing offshore wind farms could lead to significant economic benefits. The study highlighted that the NPV of such hybrid systems could be positive under various subsidy scenarios, with the most favourable outcomes occurring when subsidies were doubled. This suggests that, with appropriate financial incentives, offshore FPV systems can be a profitable investment, particularly when combined with other renewable energy technologies like offshore wind.

Scaling FPV technology, particularly for offshore environments where it can be integrated with existing offshore wind farms, demonstrates economic potential. This approach would involve developing standardized, modular solar units. Such integration could enable the development of gigawatt-scale (GW) farms, significantly increasing the overall energy output of offshore renewable energy installations (Golroodbari et al., 2021).

The scalability of floating PV systems is particularly promising in offshore settings, where vast expanses of water provide ample space for large-scale installations. By utilizing the existing infrastructure of offshore wind farms, such as grid connections and maintenance facilities, floating PV systems can be deployed more efficiently and cost-effectively. However, challenges remain in terms of structural design, durability in harsh marine environments, and the development of flexible, wave-resistant PV systems (Golroodbari et al., 2021).

2.2.4 Hybrid Systems: Wind and Solar Integration

Hybrid offshore wind and solar energy farms combine two complementary RES to enhance offshore renewable energy production. This integration addresses one of the primary challenges of offshore wind farms: the variability of wind energy production. By incorporating floating solar PV systems, hybrid systems leverage the complementary nature of wind and solar resources, as wind energy typically peaks during colder months and at night, while solar energy is abundant during daylight hours, especially in summer (Huang & Iglesias, 2024).

One of the primary benefits of integrating wind and solar systems is the shared infrastructure, which can significantly reduce costs. By co-locating wind turbines and solar panels, operators can share grid connections, mooring systems, and maintenance crews, leading to lower operational and CAPEX. The use of floating solar PV systems in offshore environments can enhance energy yield compared to standalone wind farms, especially in regions where wind resources are expected to decline due to climate change (Huang & Iglesias, 2024). The shared infrastructure, such as grid connections, mooring systems, and operational and maintenance crews, significantly reduces the Levelized Cost of Energy (LCOE). The hybrid approach minimizes the need for additional marine space, making optimal use of the vast unused areas between wind turbines and reducing the environmental footprint of energy generation (Costoya et al., 2020).

Another advantage is the potential for increased system resilience. Solar arrays can alter local wave height distributions, potentially reducing wave forces on wind turbine foundations. This protective effect mirrors the benefits observed in hybrid wind-wave systems, where wave energy converters also provide structural protection. Overall, these synergies make hybrid wind-solar farms a promising solution for sustainable and efficient offshore renewable energy production (Huang & Iglesias, 2024).

The selection of optimal size ratios for hybrid wind and solar integration is primarily driven by a trade-off between the utilization factors of the renewable generator and the electrolyser, which exhibit opposing trends. When the size of the RES relative to the electrolyser is increased, the utilization of the electrolyser (UEL) improves, but the utilization of the RES (URES) declines, and vice versa. The optimal ratio is determined by balancing these factors to achieve the lowest LCOH. The investment costs of both the electrolyser and the RES significantly influence the optimal size ratio. A decrease in RES investment costs makes it more economical to install larger renewable generators, increasing electrolyser utilization and reducing its cost share. Conversely, a reduction in electrolyser costs leads to a lower optimal RES ratio, as the system can afford to operate the electrolyser at lower utilization levels while maximizing RES usage. Looking ahead, as electrolyser costs are projected to decrease more rapidly than RES costs, the optimal RES-to-electrolyser ratio is expected to decline, making the cost-optimal design increasingly favourable for lower RES oversizing (Marocco et al., 2024).

2.3 Energy Storage Systems for Offshore Hydrogen Production

Offshore energy storage systems face different requirements and unique challenges compared to onshore systems. The remoteness of offshore facilities, their limited or non-existent connection to energy grids, and environmental restrictions present specific challenges to system architecture (Arellano-Prieto et al., 2022). Energy storage systems function as an energy buffer between wind turbine generators and electrolyzers, stabilizing power fluctuations to protect electrolyser cells from rapid degradation. Additionally, the inclusion of storage reduces the maximum current demand, enabling a more compact electrolyser design.

Offshore platforms typically require maximum power levels in the range of tens of megawatts. This is significantly lower than the typical hundreds of megawatts needed for land-based storage systems. The relatively smaller scale of offshore platforms necessitates storage solutions tailored to these reduced power demands. One of the most significant challenges for offshore energy storage is the limited availability of space and the strict weight restrictions onboard platforms. These constraints necessitate the development of compact and lightweight storage solutions that can be integrated into existing offshore infrastructure without compromising stability or operational efficiency (Arellano-Prieto et al., 2022).

Offshore energy storage systems must incorporate advanced features to ensure operational reliability and grid stability. These include black-start capabilities, continuous voltage support, and frequency regulation. Such features are critical for maintaining the stability of offshore power systems, particularly in remote locations where grid support is minimal or absent. Given the high operational costs associated with offshore environments, energy storage technologies must be designed to withstand harsh conditions while minimizing maintenance requirements. Offshore systems need to be sturdier and more resilient than onshore systems to ensure long-term reliability and cost-effectiveness (Arellano-Prieto et al., 2022).

Wind power output fluctuations lead to periods of excess production and times of low or no generation. To address this issue, energy storage systems, such as batteries and supercapacitors, are essential to balance the production process and ensure a more stable hydrogen output. Without an energy storage solution, the electrolyser system would need to be oversized to accommodate peak energy production, which would significantly increase costs. While electrolyzers can reduce their operation during low-power periods, they are unable to manage peak loads efficiently. If excess energy is generated without proper storage, it cannot be effectively utilized, leading to inefficiencies in the overall hydrogen production system (Arellano-Prieto et al., 2022).

Beyond stabilizing hydrogen production, an energy storage system is crucial for the platform itself. Various systems on the platform, including safety mechanisms, monitoring equipment, and auxiliary operations, require a stable and reliable energy supply. A dedicated energy storage system ensures uninterrupted power for these essential functions, making it a nearly mandatory component for safe and efficient operation.

2.3.1 Hybrid Energy Storage Systems

Hybrid Energy Storage Systems (HESS) provide significant advantages in overcoming the limitations of standalone energy storage technologies, particularly in standalone microgrids powered by RES. These systems integrate different energy storage technologies, such as batteries and supercapacitors, to leverage their complementary characteristics. Batteries are known for their high energy density, making them ideal for low-frequency and long-duration energy demands. Conversely, supercapacitors exhibit high power density and rapid response times, enabling them to efficiently manage high-frequency power fluctuations. This combination optimizes the performance, lifespan, and economic feasibility of energy storage solutions (Jing et al., 2017).

The working principle of HESS involves the coordinated operation of different energy storage elements through an Energy Management System (EMS). The EMS optimizes the power flow between the battery and supercapacitor, ensuring that each component operates within its optimal range. For instance, the EMS can allocate high-frequency power fluctuations to the supercapacitor, thereby reducing the stress on the battery and extending its lifespan. This decoupling of power demands not only improves overall system efficiency but also enhances the reliability and robustness of the microgrid (Jing et al., 2017).

The advantages of hybrid solutions include improved power quality, extended battery lifespan, and enhanced system reliability. By dynamically distributing high-frequency and low-frequency power exchanges between supercapacitors and batteries, HESS reduces the stress on batteries caused by rapid charge and discharge cycles. This reduction in stress is crucial for minimizing battery degradation, leading to longer operational lifespans. Additionally, hybrid systems enhance power quality by mitigating voltage fluctuations and providing a stable energy output, which is essential for the reliable operation of standalone microgrids (Jing et al., 2017). A compiled comparison of different energy storage methods can be found on Table 4.

Table 4. Energy storage method comparison

Parameter	**Battery Technologies**	**Supercapacitors**	**Internal Combustion Engine (ICE)**
Primary Role	Long-term energy storage, sustained power delivery	Rapid power absorption/release for transient demands	Backup power generation; paired with storage for load optimization
Energy Density	High (150–250 Wh/kg for Li-ion)	Low (5–10 Wh/kg)	Very high (fuel-based, e.g., diesel: ~12,000 Wh/kg)
Power Density	Moderate (250–340 W/kg for Li-ion)	Very high (up to 10,000 W/kg)	Moderate (varies with engine size)
Response Time	Seconds to minutes	Milliseconds	Seconds to minutes
Cycle Life	1,000–5,000 cycles (Li-ion)	100,000+ cycles	Limited by mechanical wear (lower than batteries)
Cost	High upfront cost	High per energy unit	Lower upfront cost but ongoing fuel/maintenance expenses
Applications in HESS	Grid stabilization, renewable integration, EV energy buffers	Frequency balancing, regenerative braking, peak shaving	Maritime hybrids, backup systems (paired with batteries for load smoothing)
Advantages	High energy capacity, scalable for long-duration storage	Ultra-fast response, high efficiency, longevity	High energy output, reliability in hybrid setups

Limitations	Slow response, degradation under high-power cycles	Low energy storage, high cost per kWh	Emissions, noise pollution, slower response compared to supercapacitors

2.3.1.1 Battery Technologies

Battery technologies play a crucial role in advancing energy storage systems, particularly for offshore applications where space, weight, and maintenance constraints are critical. A Battery Energy Storage System (BESS) typically comprises batteries, a Control and Power Conditioning System (C-PCS), protection mechanisms (e.g., HVAC for temperature control), and electronic interfaces with the grid (Arellano-Prieto et al., 2022).

BESS operates by converting electrical energy into chemical energy during charging and reversing the process during discharging. The batteries consist of stacked cells that store energy chemically, with the desired voltage and current levels achieved through series and parallel configurations. The C-PCS interfaces the batteries with the grid or load, regulating charge and discharge cycles to ensure efficient energy delivery (Divya & Østergaard, 2009).

The benefits of BESS are multifaceted. Firstly, they enhance power system reliability and stability by responding rapidly to fluctuations in supply and demand. This is particularly important in renewable energy systems, where generation can be intermittent. Secondly, BESS improves power quality by mitigating voltage sags, swells, and frequency deviations. Thirdly, they offer economic benefits through energy arbitrage—storing energy when prices are low and selling it when prices are high—and by deferring costly upgrades to transmission and distribution infrastructure. Additionally, BESS provides ancillary services such as frequency regulation, spinning reserve, and black start capabilities, all of which are essential for maintaining grid stability (Divya & Østergaard, 2009).

2.3.1.2 Supercapacitors

A key component of the proposed offshore hydrogen production system is supercapacitor storage, which enhances reliability and extends the lifespan of both electrolyzers and battery storage by absorbing wind power fluctuations. However, current supercapacitor technology remains expensive and relies on materials that are not environmentally friendly.

Supercapacitors (SCs), also known as ultracapacitors or electric double-layer capacitors (EDLCs), have emerged as a promising energy storage technology due to their unique characteristics, such as high-power density, long cycle life, and rapid charge-discharge capabilities. Unlike conventional batteries, supercapacitors store energy through electrostatic charge transfer at the interface between the electrolyte and electrodes, making them highly efficient for applications requiring quick bursts of energy (Zhang et al., 2018).

The energy storage mechanism in supercapacitors relies on the formation of a double-layer capacitor structure at the interface between electrodes and the electrolyte. Structurally, a supercapacitor consists of two electrodes separated by a membrane and impregnated with an electrolyte. The membrane facilitates ion mobility while preventing direct electrical contact. The core mechanism involves the electrostatic accumulation of charge at the electrode-electrolyte interface, augmented by reversible Faradaic reactions on the electrode surface. These Faradaic reactions contribute to total capacitance, enhancing energy storage capability without the phase or compositional changes typical of batteries (Zhang et al., 2018).

2.3.1.3 Internal Combustion Engine

The integration of hydrogen internal combustion engines (H2-ICEs) as a backup power supply in offshore hydrogen power plants presents a promising solution to address the challenges of maintaining continuous power during periods of calm wind. The study by

Niklaus et al. (2024) evaluates the feasibility of using H2-ICEs for backup power in offshore wind turbines producing hydrogen. The findings suggest that H2-ICEs provides a robust and maintenance-friendly solution, especially when combined with a battery storage system (Niklaus et al., 2024).

One of the primary advantages of H2-ICEs is their robustness and familiarity in terms of maintenance and operation. H2-ICEs are resilient to impurities in hydrogen and maritime conditions (Niklaus et al., 2024). This robustness is crucial for offshore applications where maintenance is challenging and costly. Furthermore, H2-ICEs are based on conventional combustion engine technology, which is well-understood and widely used in various industries, including automotive and marine sectors. This familiarity reduces the learning curve for maintenance personnel and ensures a higher level of reliability (Niklaus et al., 2024).

In terms of practical implementation, the world's first 100% hydrogen backup power solution, as reported by Clarke Energy (2023), demonstrates the viability of using hydrogen-powered engines for backup power. This solution, which utilizes a hydrogen-fuelled gas engine, provides a reliable and efficient backup power source, showcasing the potential for similar applications in offshore environments. The successful deployment of such systems onshore provides a strong foundation for their adaptation to offshore conditions, where the need for reliable backup power is even more critical due to the isolation and harsh environmental conditions.

However, there are challenges to consider like regular maintenance and potential component replacements are necessary to ensure long-term reliability. Additionally, the space constraints on offshore platforms necessitate compact and efficient system designs. The study by Niklaus et al. (2024) suggests that both H2-ICE and fuel cell systems can be accommodated within a 10ft sea container, but the larger cooling systems required for fuel cells may pose additional challenges.

2.3.2 Energy Storage Performance Metrics

Energy efficiency metrics are critical for assessing the operational effectiveness of energy storage systems. Depth of Discharge (DoD) measures the ratio of electrical energy released in a single discharge cycle relative to the total storage capacity. Average energy density is calculated as the rated capacity divided by the total mass of energy storage units, providing insights into the energy stored per unit mass. Other key indicators include overall power station efficiency, defined as the ratio of on-grid to off-grid electricity, and the power plant energy storage loss rate, which quantifies energy lost during storage (Zhang et al., 2024).

Reliability metrics evaluate the dependability and robustness of energy storage systems. The coefficient of unplanned outage measures the ratio of unplanned outage time to total operational time, reflecting system stability. Another crucial reliability indicator is the loss rate of energy storage equipment, which accounts for energy losses due to internal resistance, conversion inefficiencies, and self-discharge. Additionally, the annual utilization rate and equivalent utilization coefficient of energy storage equipment provide insights into the actual usage and operational efficiency of the storage systems (Zhang et al., 2024).

Regulation metrics assess an energy storage system’s ability to respond to grid demands and maintain stability. The dispatch response success rate measures the probability of successfully completing scheduling tasks after receiving commands. The dispatch response time pass rate evaluates the likelihood of responding within a specified timeframe, with a target of maintaining response times under 200 milliseconds. Peaking capacity, defined as the difference between maximum and minimum technical outputs, and Automatic Generation Control (AGC) availability, which measures the proportion of time the AGC system operates normally, are also essential indicators of regulatory performance (Zhang et al., 2024).

Economic metrics provide a financial perspective on energy storage system performance. A key measure is the O&M cost per unit capacity, which quantifies the expenses required to maintain generation equipment or power systems efficiently (Zhang et al., 2024).

Environmental metrics assess the ecological impact of energy storage systems. CO_2 intensity measures CO_2 emissions per unit of generated electricity, offering insight into the environmental footprint of energy storage operations. The retired battery step-use rate evaluates the proportion of decommissioned batteries that are repurposed, promoting sustainability. Additionally, noise level, measured in decibels, assesses the acoustic impact of energy storage stations on surrounding environments and communities (Zhang et al., 2024).

2.4 Decentralized Control

The primary objectives of the control system in island DC grids are to stabilize the grid, regulate the voltage level near its nominal value, and ensure efficient operation by preventing over-stressed units through proper power management. To achieve these goals, various coordinated control schemes, such as decentralized, centralized, and distributed control, have been proposed. These schemes rely on communication between units to maintain coordination and optimize performance.

This thesis focuses on decentralized control, which refers to a method of managing power sharing and voltage regulation in microgrids without reliance on a centralized controller or communication network. This approach distributes the control functions across individual components within the microgrid, such as sources and interlinking converters. Each component independently adjusts its operation based on local measurements, such as voltage or frequency deviations, to achieve global objectives like accurate power distribution and stable voltage regulation (Baharizadeh & Karshenas, 2024).

By eliminating reliance on a central controller, decentralized control removes single points of failure, enhancing system reliability and resilience. Despite operating independently, the system maintains robust coordination across the microgrid, ensuring efficient and stable operation (Baharizadeh & Karshenas, 2024).

2.4.1 Decentralized Control Approach

Decentralized control systems in offshore DC grids with RES offer significant advantages in scalability, reliability, and cost-effectiveness. By eliminating the need for digital communication links, these systems reduce vulnerabilities to communication delays and failures, a critical concern in offshore environments. Instead, localized decision-making allows each power unit to operate autonomously based on real-time local measurements, enhancing system responsiveness and operational flexibility. This is particularly beneficial for integrating variable RES, as decentralized control enables efficient power-sharing and load balancing without requiring centralized oversight (Habibullah et al., 2021).

One of the key benefits of decentralized control is scalability. As offshore RES installations expand, the system can seamlessly accommodate additional generators, storage units, and loads without requiring extensive modifications to the existing control infrastructure. This modularity also facilitates the integration of new technologies, ensuring adaptability to evolving energy demands and sustainability goals. Additionally, removing centralized communication systems lowers installation and maintenance costs, making decentralized setups more economically viable for offshore applications (Habibullah et al., 2021).

Decentralized systems also enhance grid stability and reliability by employing techniques such as droop control to manage voltage and dynamically balance power-sharing. Their robust architecture ensures continued operation even under fault conditions or fluctuations in RES output, common challenges in offshore environments. This resilience is crucial for maintaining power quality and minimizing operational disruptions, especially in islanded grids or during adverse weather conditions (Habibullah et al., 2021).

2.4.2 Techniques

Droop control is a widely adopted decentralized strategy for managing offshore DC grids due to its simplicity and effectiveness in integrating distributed RES. One of its key advantages is efficient power sharing among multiple wind turbines and converters without requiring digital communication links. Additionally, droop control plays a crucial role in voltage regulation, dynamically adjusting the power output of individual units in response to DC-link voltage deviations, ensuring system stability and reliability under fluctuating generation or load conditions (Habibullah et al., 2021).

A major benefit of droop control is its scalability, making it well-suited for offshore applications. It can be implemented across various power sources, including distributed generators and energy storage systems, offering flexibility and adaptability as the grid expands. This modularity allows for the seamless integration of new units or technologies, further enhancing grid resilience (Habibullah et al., 2021).

Direct Frequency Control (DFC) is a decentralized strategy designed specifically for offshore wind farms (OWFs) connected to HVDC links via diode rectifiers. This approach focuses on frequency regulation by aligning the capacitor voltage vector with a rotating reference axis at the desired reference frequency. This alignment ensures effective frequency control within the offshore grid, which is essential for the proper operation of the diode rectifier and overall system stability (Cardiel-Alvarez et al., 2018).

A key feature of DFC is its frequency-reactive power droop control mechanism, which enables synchronization of all wind turbine generator systems without requiring direct communication. By dynamically adjusting frequency based on reactive power deviations, DFC ensures equal power sharing among turbines, preventing any single unit from exceeding its reactive power limits, thereby reducing the risk of instability or equipment damage (Cardiel-Alvarez et al., 2018).

DFC also demonstrates robust performance under various operating conditions, including start-up procedures and fault events. It effectively manages transient disturbances, such as sudden changes in wind power generation or grid faults, while maintaining frequency stability and reactive power balance. This fault tolerance is particularly valuable for remote offshore wind farms, where maintenance and repairs are challenging (Cardiel-Alvarez et al., 2018).

Decentralized Model Predictive Control (DMPC) is an advanced decentralized control strategy designed to ensure precise power sharing among distributed generation units (DGUs) while maintaining DC bus voltage regulation (Karami et al., 2021). The DMPC approach replaces the conventional primary control layer, which typically includes inner loops and droop control, with a single optimal controller. This controller utilizes a predictive model of the system to anticipate future states and optimize control actions, accordingly, ensuring both accurate current sharing and voltage regulation.

DMPC has been proposed as an effective solution to ensure power sharing among DGUs while regulating the DC bus voltage (Karami et al., 2021). The DMPC approach replaces the conventional primary control layer, which typically includes inner loops and droop control, with a single optimal controller. This controller utilizes a predictive model of the system to anticipate future states and optimize control actions, ensuring both accurate current sharing and voltage regulation. Additionally, the DMPC approach provides a fast dynamic response and eliminates steady-state errors, which are common limitations in conventional droop control methods (Karami et al., 2021).

2.5 Techno-economic Analysis

The optimization of the techno-economic analysis (TEA) focuses on key project components, including wind turbines, electrolyser stacks, batteries, supercapacitors, and power converters. This approach aims to minimize CO_2 emissions and address the intermittent nature of RES. Generally, TEA is conducted to determine the optimal size and configuration of electrical load components by evaluating metrics such as NPV and the LCOH. It also assesses the sensitivity of key parameters, such as electricity prices, CAPEX, operating expenses (OPEX), and hydrogen demand, to the system's economic performance.

To achieve cost-effectiveness and system reliability, the TEA employs an integrated simulation-optimization framework designed to minimize total system costs or maximize revenue from generated electricity while meeting demand requirements. Proper component sizing is prioritized to ensure high efficiency. An optimization model is developed to determine the ideal system configuration, ensuring the lowest investment cost while maintaining optimal performance. Key decision variables in this process include wind power capacity, electrolyser efficiency, and energy storage components.

2.5.1 Life Cycle Assessment

Life Cycle Assessment (LCA) is an environmental management methodology that evaluates the potential environmental impacts associated with a technical system throughout its entire lifecycle, in accordance with ISO 14040 and ISO 14044 standards. This comprehensive approach considers all inputs and outputs related to products, facilities, and services, extending from the extraction of raw materials to their final disposal. By analysing these interactions, LCA serves as a valuable tool for decision-makers and facilitates improvements in manufacturing processes and sustainability strategies (Guven, 2024).

The LCA process is structured into four interrelated phases, beginning with the definition of the study's goal and scope. This initial phase establishes the purpose of the assessment, delineates the system boundaries, and identifies the functional unit, which provides a reference point for comparisons. Following this, the life cycle inventory (LCI) phase involves the systematic collection of data on material and energy flows associated with the system under investigation. This step is crucial for quantifying inputs such as raw materials and energy consumption, as well as outputs, including emissions and waste generation (Guven, 2024). A visual example of LCA framework is pictured in Figure 3.

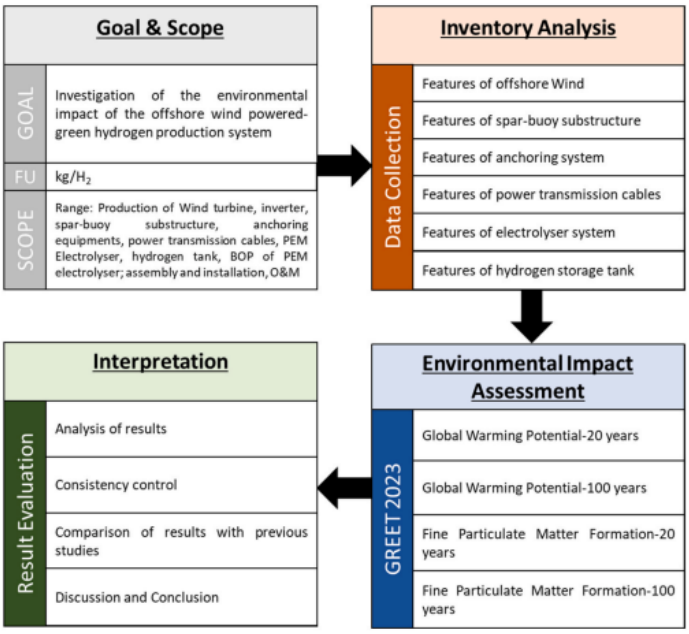


Figure 3. Example of LCA framework (Guven, 2024)

Once the inventory data has been compiled, the analysis proceeds to the life cycle impact assessment (LCIA) phase, where the potential environmental consequences of the system's inputs and outputs are evaluated. This phase provides deeper insights into environmental stressors such as greenhouse gas emissions, resource depletion, and pollution. The final phase, interpretation, involves critically examining the results, drawing conclusions, and formulating recommendations based on the objectives of the study. This stage ensures that the findings are both meaningful and applicable to improving environmental performance (Guven, 2024).

Life Cycle Cost Analysis (LCCA) is a methodological approach utilized to assess the total expenses associated with a system over its operational lifespan. In this thesis LCCA can be employed to evaluate the cumulative costs related to a proposed hydrogen production system, encompassing both CAPEX and operational expenditures (OPEX). The CAPEX investment includes initial installation and infrastructure costs, while OPEX primarily consist of maintenance fees and other recurring expenditures.

2.5.2 Levelized Cost of Hydrogen

LCOH is a key metric used to evaluate the economic viability of hydrogen production from offshore wind farms. In the study by Pegler, Rawlinson-Smith, and Greaves (2023), the LCOH is calculated to assess the cost-effectiveness of producing hydrogen from a dedicated 510 MW offshore wind farm located off the east coast of the UK. The base model returned an LCOH of £5.69 per kilogram of hydrogen (kg.H_2) at a discount rate of 6% and 100% availability.

The LCOH is calculated using a modified version of the Levelized Cost of Electricity (LCOE) formula, adapted to account for hydrogen production. The formula for LCOE is expressed as:

$$LCOE = \frac{\sum_{T}^{N} \frac{I_T + M_T + F_T}{(1+r)^T}}{\sum_{T}^{N} \frac{E_T}{(1+r)^T}} €/MWh \tag{8}$$

The formula for LCOH is expressed as:

$$LCOH = \frac{\sum_{T=1}^{N} \frac{I_T + M_T}{(1+r)^T}}{\sum_{T=1}^{N} \frac{H_T}{(1+r)^T}} €/kg.H^2 \tag{9}$$

Where N*(*)* is the expected life of the power generating facility in years, T is the operating lifetime (<N), r is discount rate (%), I_T is annual investment (Devex & Capex) (€/T(yr)), M_T is annual expenditure (Opex & Decex) (€/T(yr)), H_T- annual hydrogen production, $F_T$is fuel cost (€/T(yr)) and E_T is the annual energy generation (MWh/T(yr))

(*) N is the years of operation when the facility is generating hydrogen. The LCOE and LCOH calculations include the years for Devex, Capex (EPIC) and Decex.

2.5.3 LCOH Significance to the Research

LCOH approach is crucial for optimizing the operation of offshore DC grids integrated with RES. LCOH provides a systematic framework to assess and enhance economic and operational efficiency in such systems. By quantifying long-term costs, including CAPEX, OPEX, and energy losses, LCOH helps identify cost-effective control strategies that ensure stability and maximize energy usage.

Decentralized control benefits from LCOH-based optimization, balancing performance and cost by considering communication infrastructure, algorithm complexity, and efficiency impacts. Given RES variability, LCOH evaluates cost-effective mitigation strategies, such as energy storage and advanced power electronics, optimizing their integration while minimizing system costs. Offshore DC grids, being long-term investments, require informed planning, and LCOH provides a comprehensive metric for assessing the long-term viability of control strategies.

2.5.3.1 Offshore Wind Capacity

LCOH is significantly influenced by the capacity and characteristics of offshore wind energy, particularly when compared to onshore wind. Offshore wind farms generally exhibit higher capacity factors due to stronger and more consistent wind speeds. This increased capacity utilization can improve electrolyser efficiency and lead to a more stable hydrogen production rate. This enhanced energy output directly impacts the LCOH by reducing the cost per unit of hydrogen produced, as the primary cost driver in electrolysis-based hydrogen production is the cost of electricity (GWEC, 2023).

Offshore wind farms, particularly those utilizing floating wind technology, can be situated in deeper waters where wind resources are more abundant. This geographical flexibility allows for the deployment of larger turbines with higher capacity factors, further driving down the LCOH. According to the Global Offshore Wind Report 2023, FOW is expected to reach commercial scale by 2030, with significant potential for cost reductions as the technology matures and supply chains become more efficient (GWEC, 2023). The report highlights that the LCOE of utility-scale offshore wind has already fallen by more than 70% over the past decade, making it increasingly competitive with fossil fuel-based energy sources.

Despite these benefits, offshore wind remains more expensive than its onshore counterpart, particularly in the short term. Onshore wind generally has lower installation and maintenance costs due to its accessibility and mature infrastructure. Moreover, land-based wind farms can often be developed in regions with existing transmission networks, reducing the need for extensive new infrastructure. This cost advantage is reflected in lower LCOH values for hydrogen production from onshore wind, especially in regions with high wind speeds and favourable permitting conditions (GWEC, 2023).

In the long term, technological advancements, economies of scale, and policy-driven incentives may significantly lower the costs associated with offshore wind. The GWEC report suggests that FOW may become a more competitive alternative, especially as supply chain efficiencies improve and infrastructure solutions evolve.

2.5.3.2 Infrastructure Costs

Infrastructure costs play a significant role in LCOH calculations, as they directly influence CAPEX and OPEX associated with hydrogen production. Offshore hydrogen production systems have significantly higher infrastructure costs compared to onshore production. These costs are due to the need for specialized equipment, such as desalination units and specialized electrolyzers, which are essential for offshore operations but add complexity and expense to the overall system (Sovacool et al., 2016).

One of the primary drivers of increased infrastructure costs in offshore hydrogen production is the requirement for desalination. Offshore wind farms are typically located in saltwater environments, necessitating the removal of salt from seawater to produce fresh water for electrolysis. Desalination units are energy-intensive and require additional capital investment, which can significantly elevate the LCOH. Furthermore, the electrolyzers used in offshore hydrogen production must be designed to withstand harsh marine conditions, including salt spray, high humidity, and mechanical stress from waves and wind. These factors contribute to higher maintenance costs and a shorter equipment lifespan, further increasing the LCOH (Sovacool et al., 2016).

The research by Sovacool et al. (2016) highlights the cost discrepancies between offshore and onshore wind farms, providing insights relevant to hydrogen production. Offshore wind farms experience significantly higher cost overruns, with a mean cost escalation of 9.6% compared to 0.8% for onshore projects. This trend suggests that offshore hydrogen production may face similar financial risks, as its infrastructure requirements add complexity and uncertainty to cost estimations. Furthermore, the study emphasizes that offshore projects involve more expensive and specialized construction processes, including seabed preparation and the installation of robust foundations, which likely contribute to higher LCOH when integrating hydrogen production (Sovacool et al., 2016).

2.5.3.3 Storage Location and Transportation

LCOH is significantly influenced by both storage locations and transportation methods. These choices affect CAPEX, OPEX, and the overall economic feasibility of hydrogen projects.

The location of hydrogen storage plays a central role in determining the LCOH. In the context of offshore wind parks, hydrogen can be stored either offshore or onshore. Offshore storage, while potentially reducing the need for immediate transportation, introduces additional complexities and costs related to the construction and maintenance of storage facilities in harsh marine environments. These costs include the need for robust infrastructure to withstand corrosive seawater and extreme weather conditions, which can escalate the CAPEX and OPEX (Lundvall, 2022). Onshore storage, on the other hand, benefits from easier access and potentially lower construction costs but may require more extensive transportation infrastructure to move hydrogen from the production site to the storage facility. The choice between offshore and onshore storage thus involves a trade-off between the costs of storage infrastructure and transportation.

Hydrogen transportation presents a complex economic trade-off, with pipelines, ships, and trucks being the primary methods. Onshore pipelines require higher initial investment costs compared to trucks but are becoming more economical as transport distances increase beyond 500 km. In contrast, offshore pipelines exhibit an inverse relationship with cost-effectiveness, becoming prohibitively expensive beyond approximately 65 km, at which point shipping is more viable (Yan et al., 2021). Given the absence of dedicated hydrogen transport ships, shipping infrastructure relies on liquefied hydrogen (LH_2) technology, which entails additional energy expenditures due to liquefaction and the risk of hydrogen boil-off losses (IEA, 2019b).

The sensitivity analysis conducted by Lundvall (2022) highlights the significant impact of transportation distance and hydrogen price on LCOH. For instance, a combined increase in both offshore and onshore distances from 100 km to 1,000 km results in an LCOH increase of approximately 12 SEK/kg H2 for most scenarios, with compressed hydrogen being the most affected due to the higher transportation costs associated with trucks and trailers. Similarly, variations in hydrogen prices can dramatically alter the economic feasibility of the project, with even small changes in price leading to significant shifts in NPV.

2.5.3.4 Geographic Factors

Geographic factors play a crucial role in determining the LCOH. The variability in wind resources across different locations significantly influences the economic feasibility of hydrogen production. The DNV (2024) study of “Potential for a Baltic Hydrogen Offshore Backbone” indicates that capacity factors for offshore wind farms vary between 38% in the northern Baltic region and approximately 50% in the southern parts, which directly impacts the efficiency and cost-effectiveness of hydrogen production (DNV, 2024).

2.5.3.5 Time Horizon

The time horizon in LCOH calculations represents the period over which costs and benefits are evaluated. In the LCOH calculations a longer time horizon generally leads to a lower LCOH, while a shorter time horizon results in a higher LCOH. The selection of a time horizon exerts a significant influence on LCOH outcomes due to various interrelated factors.

Technological advancements play a pivotal role in shaping cost trajectories over extended periods. Improvements in offshore wind technology and hydrogen production processes, particularly electrolysis, are anticipated to yield substantial cost reductions. The Scottish Offshore Wind Green Hydrogen Opportunity Assessment underscores that increasing electrolyser efficiency and enhancing offshore wind turbine capacity contribute to lower LCOH over time (Scottish Government, n.d.).

The effects of economies of scale further emphasize the importance of a longer time horizon. As offshore wind and green hydrogen projects expand, CAPEX and OPEX are expected to decline due to mass production, optimized supply chains, and the accumulation of industry expertise. Notably, the assessment highlights that large-scale deployment over a 10- to 20-year timeframe could lead to considerable cost savings (Scottish Government, n.d.).

Policy and market dynamics also exhibit a strong correlation with the selected time horizon. Long-term governmental incentives, carbon pricing mechanisms, and the growth of hydrogen demand enhance the economic feasibility of offshore hybrid projects. The Scottish Government's assessment stresses the necessity of stable policy frameworks to foster long-term investment and mitigate financial risks associated with green hydrogen ventures (Scottish Government, n.d.).

Infrastructure development constitutes another critical determinant of LCOH reductions over time. The establishment of offshore wind farms and the supporting hydrogen transportation and storage infrastructure necessitates significant initial investment. However, early-stage infrastructure investments contribute to long-term cost reductions by facilitating efficient hydrogen production and distribution networks, as noted in the Scottish Government's assessment (Scottish Government, n.d.).

The concept of learning rates, which describes the cost reductions achieved through cumulative deployment and experience, further reinforces the significance of an extended time horizon. The Scottish Offshore Wind Green Hydrogen Opportunity Assessment indicates that continued deployment of offshore wind and electrolysis technologies could drive down LCOH significantly by 2040 through iterative improvements and process optimizations (Scottish Government, n.d.).

2.5.3.6 Discount Rate

The discount rate is a critical determinant in the LCOH, as it reflects both the time value of money and the cost of capital. Over recent years, the macroeconomic environment has undergone a significant shift, with global interest rates rising from historically low or even negative levels to approximately 4% in many advanced economies. This transition has had major impacts for the discount rates applied in LCOH models, thereby influencing the economic feasibility.

The relationship between discount rates and LCOH is ultimately tied to the financing structure of hydrogen production facilities. A higher discount rate increases the weighted average cost of capital (WACC), elevating the financial burden associated with upfront investments in infrastructure. For projects with lower capital expenditures and shorter payback periods, such as small-scale hydrogen production or certain retrofitting initiatives, the effect of rising discount rates may be less pronounced (CohnReznick 2024).

Moreover, the shift in discount rates influence the investment decisions. When interest rates were low, investors were more willing to finance long-term renewable energy and hydrogen projects due to the lower cost of borrowing. As rates have increased, the financial attractiveness of these projects has been lower. This creates challenges for hydrogen project developers, who have to secure financing at higher costs while ensuring that their projects remain economically viable. Some developers have responded by reassessing economic models, adjusting project timelines, or seeking alternative funding mechanisms to mitigate the effects of rising financing costs (CohnReznick 2024).

2.5.4 Policy Incentives and Funding Instruments in the European Union

Policy incentives play a crucial role in the early stages of market development for offshore hybrid RES projects. However, it's important to note that while these incentives are essential for market creation and growth, they also carry the risk of market distortion. The goal is to create an environment that can eventually mobilize private capital and reduce dependency on public finance.

The EU’s strategy for green energy emphasizes offshore renewable energy as essential to achieving climate neutrality by 2050. The strategy highlights the need to expand offshore renewables to 111 GW by 2030 and to 317 GW by 2050, with an emphasis on technological leadership, regulatory support, and investment in infrastructure (European Commission, 2023, p. 2). The policies focus on integrating offshore renewables into the broader energy market through improved grid infrastructure, fast-tracked permitting, and enhanced regional cooperation (European Commission, 2023, p. 5).

Offshore wind energy is central to the EU’s decarbonization strategy. The Commission outlines specific targets: at least 60 GW of offshore wind capacity by 2030 and 300 GW by 2050 (European Commission, 2023, p. 3). The strategy includes key measures such as:

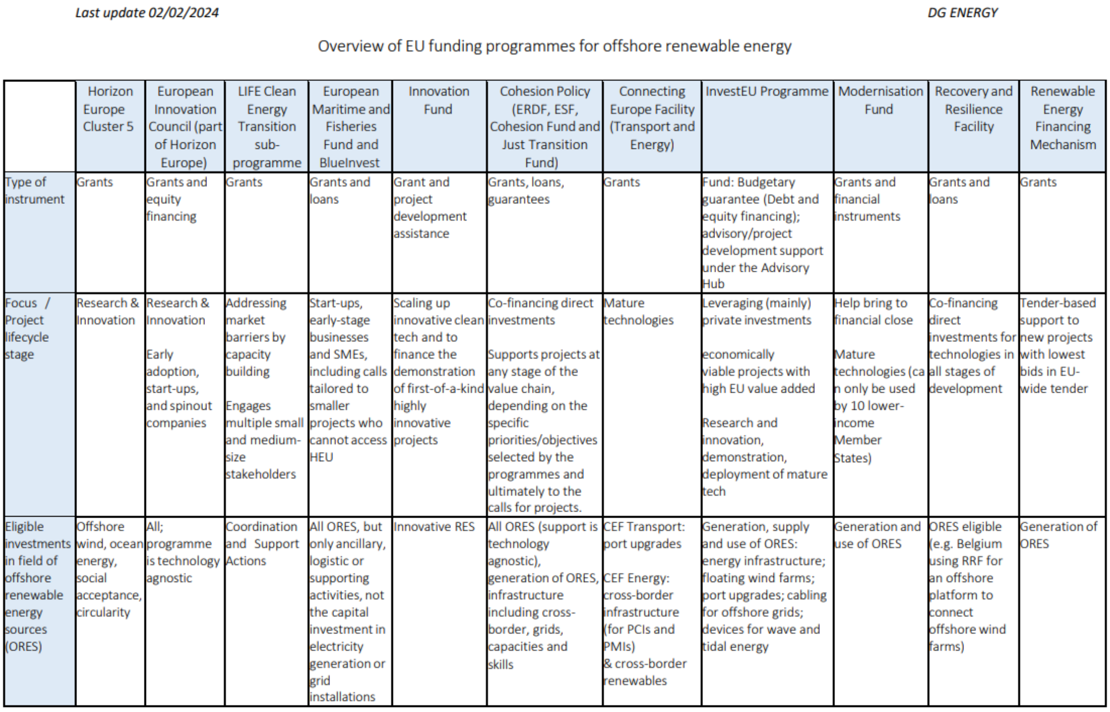
- Developing cross-border offshore grids to improve cost-benefit allocation and energy security.

- Strengthening maritime spatial planning to ensure sustainable coexistence with other industries.
- Accelerating project permitting to meet installation targets.
- Enhancing supply chains and investment to support manufacturing and deployment.
- Improving cybersecurity and resilience of offshore infrastructure (European Commission, 2023, p. 6).

EU policies significantly shape the landscape of RES projects by influencing investment conditions, regulatory frameworks, and supply chain development. One of the most impactful measures is the REPowerEU Plan, which accelerates renewable energy deployment through financial support and policy reforms (European Commission, 2023). This initiative, along with the Green Deal Industrial Plan**,** offers subsidies and tax incentives to encourage investment in offshore wind and green hydrogen production (European Commission, 2023, p. 4).

2.5.4.1 Funding Instruments

RES projects, particularly in offshore energy, require substantial financial resources to support research, development, and deployment. Given the high initial investment and long payback periods, various funding instruments play a crucial role in determining the economic feasibility of these projects. The EU offers multiple financial mechanisms tailored to different project stages, including research, scaling, infrastructure development, and commercial deployment. Each funding instrument has distinct implications for project economics, affecting costs, risks, and overall financial sustainability (European Commission. 2024). Overview table of different EU funding programmes for offshore renewable energy can be found in Figure 4.



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DG ENERGY

Overview of EU funding programmes for offshore renewable energy

	Horizon Europe Cluster 5	European Innovation Council (part of Horizon Europe)	LIFE Clean Energy Transition sub-programme	European Maritime and Fisheries Fund and BlueInvest	Innovation Fund	Cohesion Policy (ERDF, ESF, Cohesion Fund and Just Transition Fund)	Connecting Europe Facility (Transport and Energy)	InvestEU Programme	Modernisation Fund	Recovery and Resilience Facility	Renewable Energy Financing Mechanism
Type of instrument	Grants	Grants and equity financing	Grants	Grants and loans	Grant and project development assistance	Grants, loans, guarantees	Grants	Fund: Budgetary guarantee (Debt and equity financing); advisory/project development support under the Advisory Hub	Grants and financial instruments	Grants and loans	Grants
Focus / Project lifecycle stage	Research & Innovation	Research & Innovation Early adoption, start-ups, and spinout companies	Addressing market barriers by capacity building Engages multiple small and medium-size stakeholders	Start-ups, early-stage businesses and SMEs, including calls tailored to smaller projects who cannot access HEU	Scaling up innovative clean tech and to finance the demonstration of first-of-a-kind highly innovative projects	Co-financing direct investments Supports projects at any stage of the value chain, depending on the specific priorities/objectives selected by the programmes and ultimately to the calls for projects.	Mature technologies	Leveraging (mainly) private investments economically viable projects with high EU value added Research and innovation, demonstration, deployment of mature tech	Help bring to financial close Mature technologies (can only be used by 10 lower-income Member States)	Co-financing direct investments for technologies in all stages of development	Tender-based support to new projects with lowest bids in EU-wide tender
Eligible investments in field of offshore renewable energy sources (ORES)	Offshore wind, ocean energy, social acceptance, circularity	All; programme is technology agnostic	Coordination and Support Actions	All ORES, but only ancillary, logistic or supporting activities, not the capital investment in electricity generation or grid installations	Innovative RES	All ORES (support is technology agnostic), generation of ORES, infrastructure including cross-border, grids, capacities and skills	CEF Transport: port upgrades CEF Energy: cross-border infrastructure (for PCIs and PMIs) & cross-border renewables	Generation, supply and use of ORES: energy infrastructure; floating wind farms; port upgrades; cabling for offshore grids; devices for wave and tidal energy	Generation and use of ORES	ORES eligible (e.g. Belgium using RRF for an offshore platform to connect offshore wind farms)	Generation of ORES

Figure 4. EU funding programmes (European Commission. 2024)

Grants are one of the most common funding instruments for RES projects. Several EU programs, such as Horizon Europe, LIFE Clean Energy Transition, the Innovation Fund, and the Modernisation Fund, provide non-repayable grants to support research, development, and deployment of innovative technologies. (European Commission. 2024).

The primary economic advantage of grants is the reduction in capital costs. By covering a portion of project expenses, grants improve financial feasibility and lower the required private sector investment. This is particularly beneficial for early-stage projects that face significant technological and financial risks. However, grant funding is often highly competitive, requiring projects to align with EU priorities and to demonstrate potential for innovation or societal impact. (European Commission. 2024).

Some EU funding programs, such as the European Innovation Council, provide a mix of grants and equity financing. This structure is particularly beneficial for start-ups, spin-out companies, and early adopters of new technologies. The economic impact of combining grants with equity financing is twofold. First, grants provide immediate funding without repayment obligations, reducing financial burdens. Second, equity financing allows for additional capital injections from public or private investors, increasing the project's financial stability. However, equity financing may lead to dilution of ownership for founders, which can affect long-term business control and decision-making (European Commission. (n.d.)).

Funding programs such as the European Maritime and Fisheries Fund, Cohesion Policy Funds, and the Recovery and Resilience Facility provide a combination of grants and loans. This approach balances financial support with accountability, ensuring that projects receive essential funding while maintaining financial discipline. The economic effect of this funding structure is increased financial flexibility. While grants help reduce initial capital costs, loans ensure that projects remain financially viable over the long term. However, the repayment obligations associated with loans introduce financial risk, requiring projects to generate sufficient revenue streams (European Commission. (n.d.)).

Programs such as the Innovation Fund and the InvestEU Programme offer project development assistance, which includes feasibility studies, technical support, and advisory services. These instruments do not provide direct capital investment but are crucial in ensuring projects reach financial close. By improving bankability and reducing investor risk, project development assistance increases the likelihood of securing further investment. While this type of support enhances project planning and risk assessment, it does not directly reduce capital costs, requiring additional financing sources to implement the project (European Commission. (n.d.)).

The InvestEU Programme and Connecting Europe Facility use debt and equity financing to leverage private sector investment. These financial instruments lower financing costs through guarantees and risk-sharing mechanisms, making RES projects more attractive to investors. From an economic standpoint, debt and equity financing reduces the reliance on public funds and encourage market-driven investment. However, these instruments require projects to generate sufficient revenues to meet repayment obligations, making them less suitable for early-stage research initiatives (European Commission). (n.d.).

The Renewable Energy Financing Mechanism operates on a tender-based system, where funding is awarded to projects with the lowest bids in EU-wide tenders. This system fosters competition and cost efficiency, ensuring that public funds are allocated to the most economically viable projects. The economic advantage of this mechanism lies in its ability to drive market-driven pricing. However, it may disadvantage emerging technologies or projects with high initial costs that struggle to compete with more established solutions (European Commission. (n.d.)).

2.5.4.2 Other Incentives

Production Tax Credits (PTC) are one of the most impactful incentives for renewable energy projects. They provide direct monetary benefits based on the amount of energy produced, making them particularly effective for wind energy and hydrogen production. For wind energy, PTC currently offers $0.015/kWh in USA, significantly improving project profitability. This credit lowers the LCOE making wind energy more competitive in the market. Similarly, the hydrogen PTC, set at $3.00/kg, can reduce the LCOH by up to 35 %, enabling green hydrogen to compete with fossil fuel-based alternatives. The economic advantage of PTCs lies in their ability to provide long-term revenue certainly, thereby attracting investment and accelerating deployment (U.S. Department of Energy, n.d.).

Investment Tax Credits (ITC) are another form of fiscal support that can significantly lower the upfront capital costs of RES projects. When applied to hybrid projects integrating wind and solar energy, ITCs help make these projects financially viable by reducing the initial investment burden. The benefit of ITCs is particularly noticeable in large-scale renewable installations where high CAPEX can deter investors. By lowering these costs, ITCs encourage the adoption of hybrid energy solutions, improving grid stability and energy reliability. However, the effectiveness of ITCs depends on stable policy frameworks, as uncertainty over their long-term availability can create investment risks (U.S. Department of Energy, n.d.).

Risk mitigation is a crucial aspect of financing RES projects, particularly in developing markets or for first-of-a-kind (FOAK) technologies. Instruments such as guarantees and credit wrapping, offered by multilateral institutions, help de-risk projects and attract private capital. These instruments lower financing costs by improving a project's credit profile, making it more attractive to lenders and investors. For example, guarantees from institutions such as the World Bank or the European Investment Bank can enable projects to secure funding at lower interest rates. The use of risk mitigation instruments can be particularly valuable for offshore wind farms, floating solar, and green hydrogen projects, where technical and financial uncertainties remain high (Agrawal, A. 2012).

While not a direct funding instrument, carbon pricing mechanisms, such as carbon taxes and emissions trading systems, indirectly support RES projects by making fossil fuel alternatives less economically attractive. Carbon pricing creates a financial incentive for companies to transition to low-carbon energy sources, increasing the competitiveness of renewables such as wind, solar, and green hydrogen. By internalizing the environmental cost of emissions, carbon pricing encourages investment in clean technologies and provides an additional revenue stream for governments, which can be reinvested in RES development. However, the effectiveness of carbon pricing depends on market stability and the level at which carbon prices are set (Delgado-Téllez et al., 2024).

2.6 Digital twin and Simulation Model

The complexity of offshore environments, coupled with the technical challenges of hydrogen production, requires advanced tools for optimization, monitoring, and management. Digital twins and simulation models have emerged as critical technologies in this domain, offering transformative capabilities for enhancing efficiency, scalability, and sustainability in offshore hydrogen production.

Digital twins and simulation models are increasingly being deployed to address the unique challenges of offshore hydrogen production. These technologies enable real-time monitoring, predictive analytics, and optimization of hydrogen production processes, from electrolysis to storage and distribution. By integrating real-world data with advanced computational models, digital twins and simulations provide a solid framework for improving operational efficiency, reducing costs, and ensuring the safety and reliability of offshore hydrogen systems (Naanani et al., 2025).

2.6.1 Electrolysis System Modelling

A digital twin in an electrolysis system is a virtual representation that mirrors the physical electrolyser in real time, integrating data from sensors, mathematical models, and control algorithms. In proton exchange membrane water electrolysis (PEMWE), digital twins help predict system behaviour, optimize performance, and improve thermal management by simulating electrochemical reactions and heat transfer dynamics. This technology enables sensor-less monitoring of critical parameters, such as reaction interface temperature, enhancing efficiency, stability, and longevity of hydrogen production systems while reducing maintenance costs and operational risks (Zhou et al., 2024).

Zhou et al. have developed a twin model for a PEMWE system in their study. The digital twin model is based on electrochemical and heat transfer principles, enabling accurate prediction of the system state through parameter identification. This model allows for sensor-less monitoring of the reaction interface temperature, which is crucial for effective thermal management in large-scale PEMWE hydrogen systems (Zhou et al., 2024).

One of the primary benefits of using a digital twin in this context is its ability to provide precise monitoring and control of the stack temperature, which is essential for preventing membrane degradation. Elevated operational temperatures can enhance the efficiency of PEMWE systems, but membrane stability declines beyond 100°C. The digital twin model helps in maintaining optimal temperatures, thereby enhancing the stability and efficiency of the system (Zhou et al., 2024).

Additionally, the digital twin model integrates electrochemistry and heat transfer, allowing for monitoring of the interface reaction temperature without the need for direct measurement, which is challenging in industrial-scale equipment. This capability addresses a significant challenge in large-scale electrolyser cells, providing a theoretical basis for effective thermal management (Zhou et al., 2024).

The model also facilitates the identification of key electrochemical and thermodynamic parameters through collected data on voltage, flow rate, temperature, and heating power. This data-driven approach improves the accuracy of the model, enabling better prediction and control of the system's performance. The digital twin model thus serves as a valuable tool for enhancing the operational stability and efficiency of PEMWE systems, offering insights into stable and efficient system operation (Zhou et al., 2024).

2.6.2 Production Optimization

Simulation models play a crucial role in optimizing offshore hydrogen production by providing accurate estimations of production rates, economic feasibility, and transport efficiency. These models enable techno-economic analyses, helping to determine the most efficient and cost-effective configurations for hydrogen production. Simulation models are particularly useful in the design phase of the projects. For example, Lundvall’s study provides a comprehensive analysis of optimizing hydrogen production from offshore wind farms using simulation models. The study focuses on the techno-economic aspects of hydrogen production, comparing different electrolyser types and compression methods. One of the key benefits of using simulation models, as demonstrated in the Lundvall’s paper, is the ability to validate and compare different scenarios accurately (Lundvall, 2022).

Real-world data integration further strengthens the reliability of simulation models by ensuring that theoretical models align closely with practical, real-world conditions. In the study by Zhao et al (2024), wind speed and temperature data were collected from a meteorological station near Norrtälje, Sweden, and adjusted to match the hub height of the offshore wind turbines used in the model. This approach allows for a more accurate representation of the wind park's power output, directly impacting hydrogen production estimates. By incorporating historical weather patterns, the study ensures that seasonal variations, wind intermittency, and temperature fluctuations are accounted for, providing a comprehensive view of how offshore hydrogen production would perform under realistic environmental conditions (Zhao et al. 2024).

Real-world data integration enables better adaptation to dynamic offshore conditions, such as storm events, seasonal wind variations, and equipment degradation over time. By using data-driven insights, simulations can be fine-tuned to account for unexpected fluctuations, improving resilience and long-term reliability. This is particularly valuable for optimizing hydrogen production strategies, determining the best operational parameters for electrolyzers, and selecting suitable energy storage and transportation methods (Zhao et al. 2024).

2.6.3 Fleet Management

Fleet management involves overseeing and optimizing a group of assets, in the context of hydrogen electrolysis, managing a fleet of electrolysers requires monitoring their performance, scheduling maintenance, and analysing operational data to enhance efficiency. A Fleet Digital Twin extends this concept by creating a virtual representation of the entire fleet. It integrates real-time data, predictive analytics, and machine learning to support decision-making, optimize maintenance schedules, and streamline operations (Alsharif et al. 2024).

At the core of the Fleet Digital Twin concept is the idea that it represents not just individual electrolysers but the entire fleet, allowing for better decision-making regarding maintenance, production, and operational strategies. The architecture is designed to be scalable, meaning new electrolysers can be added without disrupting operations.

Additionally, it enables predictive maintenance by analysing data from multiple units to estimate degradation and optimize maintenance schedules, ultimately reducing downtime and maintenance costs (Alsharif et al. 2024).

2.6.4 Benefits and Capabilities

Digital twins and simulation models bring several significant advantages to offshore hydrogen production, enhancing efficiency, safety, and economic viability. One of the key benefits of these technologies is their ability to support predictive maintenance for electrolysis systems. By continuously monitoring system performance and utilizing advanced data analytics, digital twins can anticipate potential failures before they occur. This proactive approach reduces unplanned downtime, minimizes maintenance costs, and optimizes overall system performance, ensuring that hydrogen production remains reliable and efficient (Naanani et al., 2025).

Digital twins also contribute to efficiency improvements in offshore hydrogen production. In related industries, these technologies have demonstrated their capacity to shorten startup times and refine operational strategies. By simulating various scenarios, digital twins help operators identify optimal process parameters, streamline workflows, and enhance energy efficiency. These capabilities are particularly valuable in offshore environments where maximizing uptime and resource utilization is essential for economic success. Through process optimization and cost reduction, these models improve the financial viability of hydrogen production, making large-scale deployment more attractive to investors and energy companies. The ability to simulate different configurations and strategies allows stakeholders to identify cost-saving opportunities while ensuring that performance and sustainability goals are met (Naanani et al., 2025).

By incorporating real-world offshore wind power production data, models generate highly accurate representations of hydrogen production that reflect actual operating conditions. This integration allows for dynamic adjustments based on fluctuating energy supply, optimizing hydrogen output while maintaining system stability.

3 Case Studies

The case study section of offshore hydrogen projects provides a detailed examination of real-world applications, challenges, and outcomes associated with the development and implementation of hydrogen production, storage, and transportation in offshore environments. Offshore hydrogen projects are gaining significant attention as the world transitions towards cleaner energy sources, aiming to reduce carbon emissions and combat climate change.

Currently, there are several ongoing offshore hydrogen projects worldwide, each contributing valuable data and insights that can inform and benefit future initiatives. These projects serve as critical learning platforms, offering practical knowledge on design, implementation, and operation in diverse offshore environments. By analysing these case studies, new projects can avoid common pitfalls, optimize their strategies, and accelerate their development timelines. Table 5. contains examples of similar offshore hydrogen projects.

Table 5. Offshore hydrogen projects

Project Name	**Location**	**Description**	**Capacity**	**Start-Up Year**	**Phase**
Nexstep Offshore Hydrogen	Dutch North Sea	1.2 MW electrolyser on an existing platform, blending hydrogen with natural gas	1.2 MW	Operational	Pilot
CrossWind BLPH	Hollandse Kust Noord Wind Farm	2.5 MW electrolyser, battery storage, floating solar, and hydrogen tank storage	2.5 MW	Q4 2025	Under construction

Sealhyfe	Off the coast of Le-Croisic, France	First offshore hydrogen production facility, producing 440 kg/day	1 MW	Q1 2024	Completed
Fleur-de-lys Green Hydrogen Hub	Quebec, Canada	Powered by offshore wind to produce green ammonia	500 GW (wind power)	TBD	Planning
PosHYdon	Dutch North Sea	Integration of offshore wind, gas, and hydrogen on Q13a-A platform	1.25 MW	Q4 2025	Onshore testing
Dolphyn	UK	Floating semi-submersible with integrated wind turbine and hydrogen production	2 MW (prototype)	Summer 2024	Development
H2Mare	Germany	Offshore wind-enabled hydrogen production	Up to 10 GW by 2035	2025	Research
Gigastack	UK (Humber region)	Large-scale electrolyser system powered by offshore wind	100 MW	End of 2025	Development

This chapter examines case studies of four pioneering offshore green hydrogen projects: PosHYdon (Netherlands), Dolphyn (UK), H2Mare (Germany), and Gigastack (UK). These projects were selected for their innovative approaches to integrating renewable energy with hydrogen production, their scalability potential, and their ability to address key technical, economic, and regulatory challenges.

The selection of these case studies is based on their unique yet complementary features, collectively providing a comprehensive perspective on offshore green hydrogen production. Each project highlights innovative solutions to critical challenges in offshore hydrogen development, demonstrating how renewable energy can be effectively harnessed in demanding marine environments. By examining these initiatives, this study identifies the technical, economic, and regulatory hurdles in offshore hydrogen production and explores the strategies used to overcome them.

3.1 PosHYdon (Netherlands)

PosHYdon is the first offshore pilot project to integrate offshore wind energy with green hydrogen production on an operational platform, located in the North Sea off the coast of the Netherlands. This pilot aims to validate the technical and economic feasibility of producing hydrogen using renewable energy in an offshore environment, while leveraging existing gas infrastructure for storage and transport (Neptune Energy, n.d.; Nel Hydrogen, n.d.).

The project is a collaborative effort involving several industry leaders, including Neptune Energy, Nel Hydrogen, and other partners. It is supported by the Dutch government and aligns with the Netherlands' national strategy to become a leader in hydrogen technology and infrastructure (Neptune Energy, n.d.). By integrating offshore wind energy with hydrogen production, PosHYdon aims to showcase a scalable and sustainable model for green hydrogen production that can be replicated in other regions.

The PosHYdon project is being implemented on Neptune Energy's Q13a-A platform. The Q13a-A platform holds the distinction of being the first fully electrified platform in the region, making it an ideal location for testing innovative energy solutions such as offshore hydrogen production (Neptune Energy, n.d.). The Q13a-A platform, located approximately 13 kilometres off the coast of Scheveningen, serves as the testbed for the PosHYdon project. The platform's electrification is powered by renewable energy from offshore wind farms, which provides the electricity required for the electrolysis process. In the test phase the setup is tested onshore, and the first tests offshore are done using electricity delivered from onshore. This setup ensures that the hydrogen produced is truly "green," as it relies entirely on RES (Neptune Energy, n.d.).

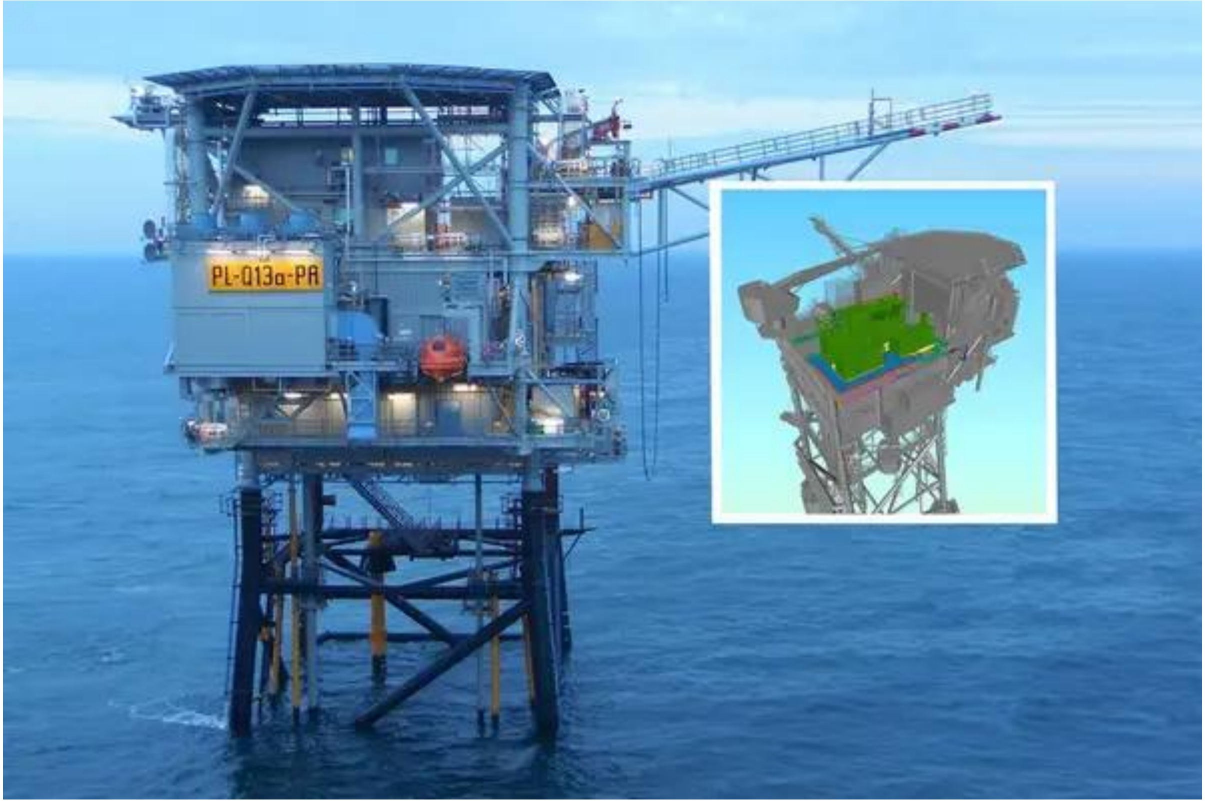

Figure 5. Neptune Energy’s Q13a-A platform (Nel Hydrogen, n.d.)

The hydrogen produced in the platform is designed to be compressed and injected into the existing natural gas infrastructure, where it is transported to shore for further use. This process not only demonstrates the feasibility of offshore hydrogen production but also highlights the potential to repurpose existing gas infrastructure for hydrogen transport and storage (Nel Hydrogen, n.d.).

3.1.1 Seawater Conversion

A key element of the PosHYdon project is the desalination process, which is crucial for converting seawater into demineralized water suitable for hydrogen production. Since electrolysis requires high-purity water to efficiently generate hydrogen, seawater needs to undergo desalination to remove salts and impurities. The PosHYdon project incorporates a reverse osmosis (RO) unit, supplied by consortium partner Hatenboer-Water, to carry out this process. The RO system ensures that seawater is purified to the necessary standards before it enters the electrolyser. The desalination system operates in three stages:

Pre-Treatment: Seawater is filtered to remove large particles, organic matter, and microorganisms that could clog or damage the reverse osmosis membranes.

Reverse Osmosis (RO): High-pressure pumps force seawater through specialized membranes that selectively allow water molecules to pass while blocking dissolved salts and other impurities.

Storage and Conditioning: The purified, demineralized water is stored in a dedicated freshwater tank before being used in the electrolysis process. Additional treatments may be applied to ensure optimal purity levels for electrolysis (Nel Hydrogen, n.d.).

3.1.2 Electrolysis

The PosHYdon project, aims to integrate a 1.25 MW electrolyser onto an active oil and gas platform. This electrolyser is designed to produce approximately 400 kilograms of hydrogen daily. The electrolyser is housed within a container on the Q13a-A platform. While its current scale is modest compared to future market demands, the planned 12-month sea trial is expected to identify technological gaps that need addressing to develop commercial offshore electrolyzers and associated energy infrastructure (Nel Hydrogen, n.d.).

Operating an electrolyser in a marine environment presents unique challenges, particularly concerning material selection and the requirement for fully remote operations. The system must withstand salt spray and associated corrosion risks from that. Additionally, maintenance and servicing intervals need to be extended, potentially up to a year, due to the logistical issues of accessing the facilities. For instance, combustible gas sensors within the electrolyser, which typically require calibration every three months, must be adapted for remote calibration to minimize the need for on-site interventions. This requires the development of systems that can be remotely managed and the usage of redundant components to ensure reliability in the event of system failures (Nel Hydrogen, n.d.).

3.1.3 Infrastructure Utilization

The PosHYdon project represents a pioneering effort to harness existing offshore oil and gas infrastructure for the production and transportation of green hydrogen. By repurposing the Q13a-A platform, the project avoids the need for constructing new offshore facilities. This approach does not only reduce costs but also accelerates the transition to hydrogen production by leveraging infrastructure that is already in place (Nel Hydrogen, n.d.).

Building new offshore structures for hydrogen production would require substantial financial investment. The PosHYdon project avoids these expenses by utilizing the Q13a-A platform, making it a more economically feasible solution for early-stage offshore hydrogen production. This strategy demonstrates how existing infrastructure can be adapted to support the green transition by offering a practical and cost-effective alternative to traditional methods (Nel Hydrogen, n.d.).

As the oil and gas industry shifts toward cleaner energy solutions, repurposing offshore platforms for hydrogen production presents a viable pathway. Rather than decommissioning these structures, they can be transformed to support green energy initiatives, thereby extending their operational lifespan and minimizing environmental impact, while lowering the lifetime investment costs.

3.1.4 Transportation

Transporting hydrogen is a critical component on the offshore hydrogen projects. Unlike traditional energy projects that require new infrastructure, PosHYdon leverages existing offshore natural gas pipelines to transport hydrogen. This approach aims to minimize the need for costly new infrastructure and accelerates the integration of hydrogen into the existing energy grid. By blending hydrogen with natural gas, the project ensures compatibility with current pipeline systems while paving the way for a gradual transition to a hydrogen-based energy economy (Nel Hydrogen, n.d.).

Constructing new pipelines specifically for hydrogen transport would entail substantial financial investment and logistical challenges. Instead, PosHYdon utilizes infrastructure that has already been built, tested, and proven reliable for natural gas transport. This approach offers several key benefits. By avoiding the need for new pipeline construction, the project significantly reduces both CAPEX and OPEX making offshore hydrogen production more economically viable. Additionally, existing pipelines can be quickly adapted for hydrogen transport, enabling faster implementation compared to building new infrastructure from scratch. The use of proven infrastructure also reduces technical risks associated with new systems (Nel Hydrogen, n.d.).

The PosHYdon project examines two primary methods for transporting hydrogen via existing pipelines. The first involves blending hydrogen with natural gas at a controlled ratio, allowing it to be transported through the same pipelines used for natural gas. This method ensures compatibility with existing infrastructure while gradually introducing hydrogen into the energy mix. The second method involves using dedicated hydrogen-ready pipelines, which are either designed or retrofitted to handle pure hydrogen. This approach is particularly useful for industrial applications requiring high-purity hydrogen. Both methods enable seamless integration of hydrogen into the existing energy system, supporting industrial use and reducing reliance on fossil fuels (Nel Hydrogen, n.d.).

The use of existing gas pipelines for hydrogen transport offers significant economic and environmental advantages in a similar manner to the usage of existing gas platforms. By repurposing existing pipelines, the project avoids the high costs associated with constructing new hydrogen-specific infrastructure, making offshore hydrogen production more financially feasible and scalable. Additionally, this approach reduces the need for additional constructions, which can have negative environmental impacts.

The success of the PosHYdon pilot project has far-reaching effects for the global energy sector. If proven viable, the approach of repurposing existing gas pipelines for hydrogen transport could serve as a blueprint for other offshore hydrogen projects worldwide. The ability to transport hydrogen through existing pipelines could significantly speed up the scaling up of offshore hydrogen production, enabling countries to harness their offshore renewable energy resources more effectively. This model could inspire similar projects in regions with extensive offshore gas infrastructure, such as the North Sea, the Gulf of Mexico, and Southeast Asia, maximizing the utility of existing assets and supporting the global transition to clean energy. Additionally, the success of PosHYdon could encourage governments and regulatory bodies to develop policies that facilitate the repurposing of gas infrastructure for hydrogen transport, creating a more favourable environment for future projects (Nel Hydrogen, n.d.).

While the use of existing gas pipelines for hydrogen transport offers numerous benefits, it also presents certain challenges that must be addressed. Not all existing pipelines are suitable for hydrogen transport due to material limitations, as hydrogen can cause embrittlement in certain metals. The optimal ratio of hydrogen to natural gas needs also to be examined to ensure safe and efficient transport, this can be examined by testing and monitoring. Furthermore, existing regulations may not fully account for the transportation of hydrogen through gas pipelines, making it essential to update regulatory frameworks to support hydrogen blending and transport.

3.1.5 Challenges

The PosHYdon project is expected to face the general challenges that most offshore hydrogen projects face. These include the corrosive offshore environment, extended maintenance intervals, remote operation and system redundancy.

Operating an electrolyser at sea presents significant challenges due to the harsh marine environment. Constant exposure to salt spray increases the risk of corrosion, which can compromise the durability and performance of critical components. To mitigate this issue, it is essential to select construction materials that are highly resistant to corrosion, ensuring the longevity and reliability of the electrolyser under extreme conditions.

Another major challenge is the need for extended maintenance intervals. Given the remote offshore location, regular service is not feasible, meaning maintenance operations may only be possible once a year. This places a high demand for the durability of components, requiring them to have long lifespans and perform reliably over extended periods without frequent human intervention.

Sensor calibration poses a unique difficulty. Certain sensors, such as combustible gas detectors, typically require calibration every three months to maintain accuracy and safety standards. However, conducting such frequent maintenance in an offshore setting is impractical. To address this, advanced solutions for remote calibration must be developed, allowing the system to function safely and effectively without the need for frequent manual adjustments.

Ensuring system redundancy is another critical factor in maintaining continuous operation. Since offshore facilities are difficult to access for immediate repairs, the system must be designed with backup components that can take over in case of failure. This redundancy minimizes downtime and reduces the need for urgent on-site intervention, enhancing the overall reliability and efficiency of the offshore hydrogen production system.

3.2 Dolphyn Project (UK)

The Dolphyn Project, developed by Environmental Resources Management company (ERM), is an innovative initiative aimed at producing green hydrogen at scale using offshore floating wind technology. The project integrates electrolysis and a wind turbine on an anchored floating substructure to generate hydrogen from seawater, powered entirely by wind energy. The primary goal of the Dolphyn Project is to deliver large-scale zero-carbon hydrogen at a competitive price, thereby contributing significantly to the UK's path to achieving Net Zero emissions as outlined in the government's ten-point plan for a green industrial revolution (ERM, 2021).

The Dolphyn Project concept employs a modular design, with each unit consisting of a floating substructure, a wind turbine, and an electrolysis system. The base configuration for deployment is a 20 x 20 array, which would provide a hydrogen production wind farm with a capacity of 4 GW. This scale of production could supply sufficient green hydrogen to heat approximately 1.5 million homes. The project is designed to operate in deep-water environments, leveraging the UK's abundant offshore wind resources, particularly in the North Sea and Celtic Sea (ERM, 2021).

Figure 6. Illustrative of Dolphyn Project configuration (ERM, 2021)

The Dolphyn Project has undergone several phases of development, including the design of a 2 MW prototype and pre–Front End Engineering Design (pre-FEED) activities for a 10 MW commercial-scale demonstrator. The 10 MW unit is expected to be operational by the late 2025, with larger commercial-scale farms (100-300 MW) planned for the late 2020s. The project aims to accelerate the deployment timeline by bypassing the need for a smaller-scale 2 MW prototype and moving directly to the 10 MW unit, thereby reducing the development pathway by up to four years (ERM, 2021).

Key components of the Dolphyn project system include a seawater lift system, a desalination unit, a hydrogen production system using Polymer Electrolyte Membrane (PEM) technology, and a standby power generation system. The hydrogen produced is stored on board at medium pressure and exported to shore via a pipeline. The system is designed to be fully autonomous, with remote operations possible from shore, minimizing the need for personnel intervention and reducing operational costs (ERM, 2021).

The Dolphyn Project also emphasizes safety and environmental considerations, adhering to strict UK legislation and internationally recognized codes and standards. The design process has been independently verified by Lloyd’s Register to ensure robust hazard management and compliance with safety regulations. The project aims to minimize environmental impact by using proven technologies and implementing inherently safer design principles (ERM, 2021).

3.2.1 Integrated Design

The modular design philosophy is central to the project, allowing for scalability, flexibility, and ease of deployment across various offshore locations. The integration of these systems into a single floating unit represents a significant advancement in offshore renewable energy technology, particularly in the context of hydrogen production.

The modular design approach simplifies the interface requirements between different systems, reducing the need for new and complex integration solutions. This is particularly important for offshore applications, where maintenance and operational efficiency are critical. By using proven technologies and modular components, the Dolphyn Project aims to minimize technical risks and increase the reliability of the system. For instance, the desalination system is designed to operate autonomously and is integrated into the floating structure. The use of reverse osmosis technology in the 2MW prototype unit, and thermal desalination in the 10MW commercial demonstrator, highlights the project's adaptability to different scales and operational requirements (ERM, 2021).

The modular nature of the Dolphyn system allows for future scalability and optimization. For example, the 10MW commercial demonstrator unit builds on the lessons learned from the 2MW prototype, with improvements in design, efficiency, and cost-effectiveness. The modular design also facilitates the deployment of multiple units in large-scale offshore wind farms, enabling the production of hydrogen at a multi-GW scale. This scalability is crucial for meeting the growing demand for green hydrogen in various sectors, including industry, transport, and heating (ERM, 2021).

3.2.2 Hydrogen Transport

The Dolphyn Project utilizes a hydrogen transport method that involves the direct export of hydrogen via a dedicated pipeline to shore. This approach is designed to maintain the purity of hydrogen, avoiding contamination from blending with natural gas, which enhances its suitability for various applications. One of the main advantages of this method is its ability to supply high-purity hydrogen directly to consumers, particularly for transport applications and industrial users. By maintaining a dedicated hydrogen pipeline, the project mitigates the risk of cross-contamination that could arise from blending hydrogen into existing natural gas infrastructure (ERM, 2021).

The dedicated hydrogen pipeline also presents challenges. While technology has proven mature in onshore applications, the main challenges come from the economic side. The economic feasibility of hydrogen pipelines depends on achieving sufficient scale to reduce the overall high capital costs associated with dedicated pipeline infrastructure build. A potential alternative to transportation of pure hydrogen through new pipelines is to blend hydrogen into the existing gas network, which is considered for future expansion in the project. While blending allows for immediate integration into current infrastructure, it reduces the purity of hydrogen available for specialized applications, such as fuel cells, and requires end-user modifications to accommodate varying hydrogen concentrations (ERM, 2021).

The Dolphyn Project is planning to construct a new hydrogen export pipeline to transport hydrogen from offshore production facilities to shore. The pipeline is designed to accommodate future expansion, with tie-in spools allowing for additional connections at the seabed. The current design includes a flexible riser connecting the Dolphyn floating substructure to the seabed, a subsea pipeline extending to a nearshore tie-in point, and a landfall section, which is planned to be a rigid steel pipeline installed through directional drilling (ERM, 2021).

A preliminary assessment has been conducted to determine the appropriate pipeline sizing for different scales of deployment, ranging from a single 10 MW unit to a large-scale hydrogen production facility of up to 300 MW. The pipeline diameter is expected to increase as capacity scales up, ensuring efficient hydrogen transport over long distances. The Dolphyn Project includes a financial assessment of hydrogen transportation via a dedicated pipeline, with a focus on long-term cost trends and scalability. The financial modelling undertaken considers the lifetime costs of hydrogen production and transport, incorporating cost estimates from key suppliers and industry benchmarks. The model evaluates how the LCOH can be reduced through economies of scale, technological advancements, and optimized OPEX (ERM, 2021).

A key economic consideration for the dedicated pipeline is its potential for cost reduction over time. The project anticipates that, by 2040, hydrogen costs could reach approximately £1.50/kg, making it competitive with other forms of energy transmission. This forecast accounts for reduced CAPEX and OPEX as production scales up, allowing the pipeline to serve larger offshore hydrogen facilities. The financial modelling suggests that pipeline transport remains the preferred option. However, the analysis also acknowledges the need for public funding and regulatory support to overcome initial financial barriers (ERM, 2021).

3.2.3 Scalability

The scalability of the Dolphyn Project is a core consideration in its development strategy. The project has been designed to be deployed in a modular fashion, enabling flexibility in scaling from small pilot projects to large-scale offshore wind farms. The base case scenario for full-scale deployment envisions a 20x20 array configuration, creating a hydrogen production wind farm with a capacity of 4 GW (ERM, 2021).

The development plan follows a phased approach, starting with a 10 MW commercial demonstrator expected to be operational in late 2025. The learnings from this initial phase will inform subsequent expansions, with projects at the 100–300 MW scale anticipated in the late 2020s, and GW-scale projects expected from the early 2030s onwards. This strategy is designed to facilitate a gradual transition toward large-scale hydrogen production while integrating advancements in technology and economies of scale (ERM, 2021).

One of the primary drivers of scalability is the project's reliance on FOW technology, which enables deployment in deeper waters where wind resources are more abundant. The efficiency of hydrogen pipelines as an energy transmission method also supports economic operations at long distances from shore, making large-scale production feasible (ERM, 2021).

3.2.4 Challenges

The ERM Dolphyn Project faces several key challenges as it moves toward commercialization. One of the most significant obstacles is the regulatory and consenting process.

Offshore hydrogen production is an emerging field, and there is no existing regulatory framework specifically designed for such projects. As a result, the project navigates in an uncharted regulatory landscape, working closely with authorities such as the Oil and Gas Authority Crown Estate Scotland and Marine Scotland to establish a formal consenting strategy. Securing permission to co-locate with an existing licensed FOW farm adds another layer of complexity, as it requires coordination with multiple stakeholders to ensure compliance with safety and environmental regulations (ERM, 2021).

While public funding has supported the project’s early development, further investment is needed to move beyond the 10MW demonstrator phase to commercial-scale deployment. The procurement, construction, and commissioning of the system will require significant financial backing, and securing the necessary capital is essential to keeping the project on schedule. The level of UK Government support, both in terms of subsidies and policy incentives, will play a critical role in shaping these agreements and ensuring that the project can compete with other hydrogen production methods (ERM, 2021).

Economic viability is another challenge that the project must overcome. At its current scale, the LCOH is slightly higher than industry benchmarks. This means that cost reductions will be necessary to make the project competitive in the energy market, scaling up production is expected to bring these costs down (ERM, 2021).

3.3 H2Mare (Germany)

The H2Mare is a flagship project in Germany aiming to advance the production of green hydrogen directly from offshore wind energy. The project is funded by the Federal Ministry of Education and Research and is part of Germany's broader efforts to implement its National Hydrogen Strategy. The project seeks to explore and develop innovative technologies for the efficient offshore generation of hydrogen and other power-to-X (PtX) products, such as methanol and ammonia, without the need for grid integration. This approach is expected to significantly reduce production costs and enhance energy security while contributing to climate neutrality (Federal Ministry of Education and Research, 2024).

Figure 7. Illustrative picture of H2Mare projects configuration (Federal Ministry of Education and Research)

The H2Mare project is structured around several key components, each focusing on different aspects of offshore hydrogen production. These include the development of self-sufficient water electrolyzers (H2Wind), the adaptation of wind turbines for hydrogen production (OffgridWind), the production of additional PtX products (PtX-Wind), and the exploration of overarching regulatory and societal acceptance issues (TransferWind). The project involves a consortium of 31 partners, including research institutions, industry leaders, and technology providers, working collaboratively to address technical, environmental, and regulatory challenges (Fraunhofer Institute for Wind Energy Systems, 2024).

One of the primary goals of H2Mare is to couple water electrolyzers directly with offshore wind turbines, thereby enabling the production of green hydrogen in a more cost-effective and sustainable manner. This direct coupling eliminates the need for extensive grid infrastructure and allows for the utilization of larger potential areas for wind energy generation. Additionally, the project aims to develop solutions for the storage, treatment, and supply of water for electrolysis, as well as to assess the environmental impact and lifecycle of the technologies being developed (Federal Ministry of Education and Research, 2024).

The H2Mare Initiative also places a strong emphasis on knowledge transfer and societal acceptance. Through projects like TransferWind, the initiative seeks to engage stakeholders, including the public, industry, and policymakers, to foster a broader understanding and acceptance of offshore hydrogen production. This includes developing regulatory frameworks, conducting ecosystem research, and creating communication strategies to promote the benefits of green hydrogen production (Fraunhofer Institute for Wind Energy Systems, 2024).

3.3.1 Power-to-X

The H2Mare project's PtX-Wind initiative is exploring offshore production of PtX products such as methanol, Fischer–Tropsch fuels, and ammonia. To achieve this, the project will extract the necessary CO_2 and nitrogen locally from the air or seawater. A key focus is on co-electrolysis of CO_2 and water, as well as direct seawater electrolysis. If successful, seawater electrolysis will eliminate the need for prior desalination (Fraunhofer Institute for Wind Energy Systems, 2024).

Initially, PtX-Wind will test these concepts onshore before demonstrating a selected approach offshore on a floating platform. The goal is to produce Fischer–Tropsch fuels that can serve as sustainable energy sources (Fraunhofer Institute for Wind Energy Systems, 2024).

3.3.2 Energy Supply for Offshore Wind Turbines in Calm Conditions

In the absence of wind, a wind turbine must maintain its energy supply even when it is not generating electricity. Conventional wind turbines achieve this by connecting to the power grid. However, in the H2Mare project OffgridWind, the offshore wind turbine operates autonomously to produce hydrogen and is not grid-connected. Instead, it relies on self-produced hydrogen for its power supply (Fraunhofer Institute for Wind Energy Systems, 2024).

There are two potential solutions for converting hydrogen into electrical energy: a hydrogen combustion engine with a generator or a hydrogen fuel cell. Fraunhofer ICT is evaluating these options based on efficiency, cost-effectiveness, and service life. In mid-2023, simulation models of the energy supply system for both energy converters were developed. Various load scenarios, such as short and extended windless periods, were defined and analysed to assess efficiency and hydrogen consumption (Fraunhofer Institute for Wind Energy Systems, 2024).

3.3.3 Water Management

Water is essential not only for hydrogen production via electrolysis but also for various PtX processes on an offshore platform. It serves as a reaction partner, a cooling medium, and plays a role in synthesizing energy carriers from CO_2 and hydrogen, where it is also a byproduct. The H2Mare projects PtX-Wind, led by the DVGW Research Centre at the Engler-Bunte-Institute (DVGW-EBI), is analysing these aspects to develop tailored water treatment solutions for all stages of PtX processes, including seawater desalination, water supply, cooling, and wastewater management (Fraunhofer Institute for Wind Energy Systems, 2024).

A key research focus is minimizing seawater extraction and developing wastewater treatment methods that allow process water to be reused in electrolysis or synthesis, supporting a zero-discharge approach. The first laboratory-scale facilities for testing process wastewater were commissioned by DVGW-EBI in summer 2023.

DECHEMA has conducted a heat balance analysis for all PtX processes to explore the potential use of excess heat from cooling water on larger offshore platforms, such as research and production facilities. Findings indicate that these platforms generate significant surplus thermal energy, which could be strategically utilized to enhance energy efficiency and optimize production processes (Fraunhofer Institute for Wind Energy Systems, 2024).

3.3.4 Challenges

One of the primary challenges is adapting to the harsh offshore conditions. The project is researching and developing electrolyzers capable of withstanding these demanding environments, which involves making necessary adaptations to both the electrolyzers and wind turbines to ensure they operate efficiently and reliably at sea.

The H2Wind sub-project is dedicated to creating compact, self-sustaining electrolysis systems that can function efficiently despite the rough conditions at sea. This includes developing processes for water treatment and hydrogen storage to ensure the system's sustainability. The OffgridWind sub-project is addressing the challenge of designing new wind turbines specifically tailored for hydrogen production. This involves setting up a dedicated test infrastructure to evaluate the best methods for combining turbines with electrolyzers.

Regulatory and safety issues are also a significant focus of the project. The TransferWind sub-project is working on issues such as regulatory framework conditions, safety, and environmental impact assessments. It also emphasizes knowledge transfer, acceptance research, and the development of concepts for a hydrogen refuelling network for ships.

3.4 Gigastack Project (UK)

The Gigastack Project is a flagship renewable hydrogen initiative in the United Kingdom, led by a consortium comprising ITM Power, Ørsted, Phillips 66 Limited, and Element Energy. Funded by the Department for Business, Energy & Industrial Strategy (BEIS) through the Low Carbon Hydrogen Supply Competition, the project aims to demonstrate the feasibility of large-scale renewable hydrogen production using electrolysis powered by offshore wind energy. The primary goal of Gigastack is to decarbonize industrial processes, particularly in the Humber region, by replacing hydrocarbon-based fuels with renewable hydrogen. This aligns with the UK's broader ambition to achieve net-zero greenhouse gas emissions by 2050 (Gigastack, 2021).

The project is structured in multiple phases, with the current Phase 2 focusing on the development of a 100-MW electrolyser system. This system will utilize renewable electricity from Ørsted's Hornsea Two offshore wind farm, the largest of its kind globally, to produce hydrogen. The hydrogen will be supplied to Phillips 66 Limited's Humber Refinery, where it will replace refinery fuel gas in industrial scale fired heaters. This transition is expected to significantly reduce carbon emissions in one of the UK's largest industrial clusters (Gigastack, 2021).

The Gigastack Project also aims to drive down the cost of electrolyser technology through advancements in manufacturing and system design. ITM Power, a key consortium member, has developed next-generation polymer electrolyte membrane (PEM) electrolysers, which are more efficient and cost-effective than previous models. The project has facilitated the construction of ITM Power's Gigafactory in Sheffield, the world's largest electrolyser production facility, which is expected to reduce electrolyser stack costs by 40% in upcoming years (Gigastack, 2021).

In addition to technological advancements, the project seeks to address regulatory and policy barriers to the widespread adoption of renewable hydrogen. This includes exploring solutions for grid connection compliance, network charges, and the development of a supportive policy framework to enable large-scale hydrogen production. The consortium has also developed a business case for renewable hydrogen, estimating the LCOH at £7.93/kgH_2 for the base case, with potential reductions to £5.11-5.44/kgH_2 under optimized conditions. By 2030, the LCOH is projected to decrease further to £2.80/kgH_2, making renewable hydrogen more competitive with traditional fossil fuels (Gigastack, 2021).

3.4.1 Next-generation stack technology

The Gigastack Project is known for its development and deployment of next-generation electrolyser stack technology, which represents a significant advancement in the field of renewable hydrogen production. At the core of this innovation is ITM Power's Gigastack Electrolyser Platform (GEP), a 5MW electrolyser module that utilizes two 2.5MW stacks to achieve a scalable and efficient hydrogen production system (ITM Power, 2021). This next-generation technology is designed to operate at a higher current density, enabling greater hydrogen to output relative to the physical size of the unit. The GEP stacks are also characterized by their rapid response capability, which allows them to adjust quickly to fluctuations in power input, making them highly compatible with the intermittent nature of RES such as offshore wind (ITM Power, 2021).

One of the key technological advancements in the GEP is the increase in the number of electrolysis membranes within each stack, achieved by making the membranes thinner and increasing their active area. This approach enhances overall hydrogen production without increasing the system’s footprint. Additionally, the new stack technology improves efficiency, raising the system’s performance from 68% (HHV) in previous designs to 73%, while also reducing water consumption from 20 litres per kilogram of hydrogen to 17 litres per kilogram. (ITM Power, 2021). The GEP stacks are designed to be modular and "plug-and-play," facilitating their integration into larger systems, such as the 100MW electrolyser facility planned for the Gigastack Project. This modularity does not only enhance the scalability of the technology but also simplifies installation and maintenance processes.

The development of next-generation stack technology has been supported by extensive testing and prototyping, including the construction and operation of a 150kW prototype system. This prototype has allowed ITM Power to validate the performance and reliability of the new stack design, ensuring that it meets the strict demands of industrial-scale hydrogen production (ITM Power, 2021). The successful scaling of this technology from laboratory testing to full-scale deployment represents a critical milestone in the commercialization of renewable hydrogen production.

Beyond efficiency and cost considerations, the modularity of the 5MW stacks enables flexible deployment, making it possible to build large-scale electrolyser systems in 100MW increments or more. In the Gigastack Project, twenty 5MW units, with an additional two for redundancy, will be integrated into the Humber Refinery facility, ensuring continuous operation at 100MW capacity. This level of scalability represents a step change in industrial hydrogen production and provides a model for future large-scale projects (ITM Power, 2021).

3.4.2 Cost Reduction

The Gigastack Project incorporates several innovative cost reduction strategies to make large-scale renewable hydrogen production economically viable. A key driver of these reductions is the integration of semi-automated manufacturing at ITM Power's Gigafactory. This transition improves efficiency, reduces labour costs, and increases manufacturing throughput, ultimately lowering the CAPEX associated with electrolyser production. A major aspect of cost reduction also lies in the design improvements of the GEP, next generation electrolyser stacks (ITM Power, 2021).

The project benefits from economies of scale as it moves from MW to GW-scale production. Scaling up electrolyser systems from small units to large 100MW deployments, spreads fixed costs over a larger output, making each unit of hydrogen produced more cost competitive. Additionally, bulk procurement of raw materials and standardized production methods further drive down costs, as larger orders result in lower unit prices for key components such as membranes, electrodes, and power electronics (ITM Power, 2021).

Another cost-saving measure involves resource efficiency, particularly in water consumption. By opting to use refinery wastewater for electrolysis rather than fresh industrial water, the project reduces the demand for costly water treatment and supply infrastructure. This approach not only minimizes operational costs but also aligns with circular economic principles, making hydrogen production more sustainable (ITM Power, 2021).

The project's overall cost competitiveness is further enhanced by its direct integration with offshore wind power from Ørsted's Hornsea Two wind farm. By securing low-cost renewable electricity directly from the source, Gigastack avoids fluctuations in grid electricity prices, reducing the LCOH. The project estimates that, hydrogen production costs could range from £5.11–5.44/kg in a low-cost scenario, with further reductions expected as the technology matures. Projections indicate that by 2030, Nth-of-a-kind projects could see LCOH fall by approximately 47%, reaching around £2.80/kg (ITM Power, 2021).

Figure 8. Picture of the Hornsea 2 (ITM Power, 2021)

3.4.3 Challenges

The current "Grid Code" and "Bilateral Connection Agreements" lack clarity on how to connect a FOAK electrolyser project with an offshore wind farm and the onshore grid. The Offshore Transmission Owner (OFTO) framework, which governs the divestment of offshore transmission assets, is not designed for co-located assets like an electrolyser and a wind farm. This creates risks around cost disallowance and revenue distribution. Network charges, such as Transmission Network Use of System and Balancing Services

Use of System, are undergoing significant reform, adding uncertainty to cost projections. Additionally, the current metering framework disincentivizes the offshore wind farm from supplying power to the electrolyser during negative price periods, which could lead to unnecessary restrictions (ITM Power, 2021).

Commercial challenges also pose significant risks to the project. CAPEX for the 100MW electrolyser facility is substantial, with total installed costs estimated at £269 million. Reducing these costs through economies of scale and technological advancements is critical for the project's financial viability. The LCOH for the Gigastack Project is currently estimated at £7.93/kgH_2 in the base scenario, with a target to reduce it to £5.11-5.44/kgH_2 in the low-cost scenario. However, this is still higher than the alternative cost of natural gas plus carbon price (£0.85/kgH_2). Closing this gap requires significant cost reductions and policy support. The project also relies on favourable Power Purchase Agreement (PPA) terms with the offshore wind farm to reduce electricity costs. Managing excess power volumes in an "Oversized PPA" scenario adds complexity and cost, which could impact the LCOH. The project relies on government financial support through mechanisms such as the Hydrogen Business Model and the Net Zero Hydrogen Fund (ITM Power, 2021).

Operational challenges also need to be addressed. The electrolyser must operate near the baseload to meet the fixed demand of the Humber Refinery, which limits the ability to take advantage of more volatile power periods that could otherwise reduce costs. Future deployments may require more flexible operation, but this is not feasible for the current FOAK project. Additionally, the project does not include large-scale hydrogen storage, which could help balance supply and demand. This limits the flexibility of the system and increases the reliance on continuous operation (ITM Power, 2021).

Technically, integrating the electrolyser with offshore wind presents difficulties, especially in managing fluctuating power supply and demand. The development of supporting infrastructure, such as high-voltage substations and hydrogen pipelines, poses logistical and permitting challenges. Additionally, the project needs to scale up from its current size to GW-level electrolysis, ensuring cost reductions while maintaining technological efficiency.

3.5 Discussion of Findings

These case studies provide valuable insights into the technological, economic, and regulatory dimensions of offshore hydrogen production, highlighting both the opportunities and challenges associated with this emerging field. By examining the strategies and outcomes of these projects, this discussion aims to identify key trends, patterns, and lessons that can inform the development of future offshore hydrogen initiatives.

The findings are organized around several critical themes, including the integration of renewable energy with hydrogen production, technological advancements, the utilization of existing infrastructure, economic viability, regulatory challenges, environmental and safety considerations, and the scalability and replicability of offshore hydrogen systems. Ultimately, this discussion seeks to contribute to the broader discourse on the role of offshore hydrogen in the global energy transition. By synthesizing the experiences of these pioneering projects, it provides a foundation for understanding how offshore hydrogen production can be scaled up and replicated across diverse regions, paving the way for a sustainable and resilient energy future.

Technological innovation is a central theme across these projects, particularly in the areas of electrolysis, water management, and PtX technologies. The PosHYdon and Gigastack projects employ PEM electrolyzers, which are favoured for their efficiency and ability to respond rapidly to fluctuations in power input from renewable sources. Gigastack has made significant strides in next-generation stack technology, achieving higher current density and efficiency (73% higher heating value) while reducing water consumption and overall costs. Meanwhile, the H2Mare project is exploring direct seawater electrolysis, which could potentially eliminate the need for desalination, a process that adds complexity and cost to offshore hydrogen production.

Water management remains a critical component in most projects, with desalination playing a key role in ensuring the availability of high-purity water for electrolysis. However, the H2Mare project is investigating innovative approaches such as seawater electrolysis and wastewater reuse to minimize freshwater consumption and enhance sustainability. Additionally, the H2Mare initiative is pioneering the production of PtX products, using CO_2 and nitrogen extracted from seawater or air. This diversification of hydrogen applications could significantly enhance the economic viability of offshore hydrogen production.

A notable trend observed in these case studies is the repurposing of existing offshore oil and gas infrastructure to support hydrogen production. The PosHYdon project, for example, utilizes the Q13a-A platform, an electrified oil and gas platform, to produce hydrogen and transport it via existing natural gas pipelines. This approach not only reduces the need for new infrastructure but also demonstrates the potential for transitioning fossil fuel assets to green energy solutions. Similarly, the blending of hydrogen with natural gas for transport through existing pipelines, as seen in the PosHYdon project, offers a practical and cost-effective solution for integrating hydrogen into the existing energy grid. Dolphyn and H2Mare are also exploring the use of dedicated hydrogen pipelines to maintain purity for industrial applications. The utilization of existing infrastructure reduces CAPEX, which remains one of the main challenges in similar projects, and it also improves economic viability over the project's lifetime.

Economic viability is a central concern for all four projects, with cost reduction being a key focus area. Technological advancements, economies of scale, and innovative manufacturing processes are driving significant reductions in the LCOH. Similarly, the Dolphyn and H2Mare projects aim to reduce LCOH through scalable designs and optimized operational strategies. While the current LCOH for offshore hydrogen production remains higher than that of traditional fossil fuels, projections indicate substantial declines by

2030. The Gigastack Project estimates that LCOH could drop to nearly one-third of its original level by 2030, driven by technological improvements and economies of scale.

Regulatory and policy challenges represent significant barriers to the widespread adoption of offshore hydrogen production. All four projects operate in a regulatory landscape that lacks established frameworks for offshore hydrogen production. The Dolphyn project, for instance, is navigating uncharted regulatory territories, working closely with authorities such as the Oil and Gas Authority and Crown Estate Scotland to establish consenting strategies. Similarly, the Gigastack Project highlights challenges related to grid connection compliance, network charges, and the need for supportive policy frameworks. Government support and funding are critical for overcoming these barriers, as evidenced by the funding provided to the H2Mare project by the German Federal Ministry of Education and Research and The Gigastack Project's reliance on UK government support through mechanisms such as the Hydrogen Business Model and the Net Zero Hydrogen Fund.

Environmental and safety considerations are paramount in the design and implementation of offshore hydrogen projects. The Dolphyn project, for example, adheres to strict UK legislation and international safety standards, with independent verification by Lloyd’s Register. Similarly, the H2Mare project conducts comprehensive environmental impact assessments and explores zero-discharge approaches for wastewater management. The use of proven technologies and inherently safer design principles is a common strategy across these projects to mitigate risks in the harsh offshore environment.
Scalability is a key design consideration across all projects, with a focus on transitioning from pilot-scale demonstrations to commercial-scale deployment. The Dolphyn project, for instance, plans to scale from a 10 MW demonstrator to a 4 GW hydrogen production wind farm, while the Gigastack project is developing modular 5 MW electrolyser stacks that can be scaled to 100 MW or more. This modular and replicable design approach provides a blueprint for other regions with similar offshore wind resources, such as the

Gulf of Mexico and Southeast Asia, enabling the widespread adoption of offshore hydrogen production.

The case studies reveal a clear trend toward integrating offshore wind energy with hydrogen production, supported by technological advancements, infrastructure repurposing, and scalable designs. A strong correlation exists between renewable energy input and the LCOH, with the integration of low-cost renewable energy directly reducing LCOH. Additionally, technological advancements in electrolyser technology and manufacturing processes are directly contributing to cost reductions and improved efficiency. Storage efficiency and system performance are also closely linked, as demonstrated by the emphasis on efficient hydrogen storage and transport systems in similar projects.

4 Conclusion and Future Work

The literature review and metadata analysis conducted within the framework of WP1 in the OptiDCG4H2 project have provided insights into the feasibility and challenges of offshore hydrogen production systems. The review highlighted the critical role of green hydrogen production methods, particularly through electrolysis powered by RES such as offshore wind and floating PV systems. The analysis underscored the importance of HESS, combining batteries and supercapacitors, to address the intermittency of RES and ensure stable hydrogen production. Furthermore, the metadata analysis revealed key factors influencing the LCOH, including system design, energy storage performance, and the integration of decentralized control systems. These findings contribute to WP1 by providing a comprehensive understanding of the technological, economic, and operational challenges associated with offshore hydrogen production, thereby laying the groundwork for subsequent project tasks.

The research presented in this thesis contributes to the field of offshore hydrogen production by analysing existing knowledge through a comprehensive literature review, enriched by the case studies. This approach not only clarifies current understanding but also identifies insights and practical implications that advance the discourse on offshore hydrogen.

One of the primary contributions of this work lies in its identification and analysis of best practices and lessons learned from real-world applications of offshore hydrogen projects. By examining a diverse range of case studies, this research provides an understanding of the operational, technical, and logistical challenges faced by existing projects. These insights are invaluable for informing the design and implementation of future offshore hydrogen initiatives. The case studies highlight successful strategies as well as common pitfalls, offering a practical framework for optimizing project outcomes.

Economic viability is a central concern for the adoption and expansion of offshore hydrogen production. By comparing multiple case studies, the study identifies key cost drivers and explores the potential for cost reduction over time. A significant finding is the economic benefits derived from economies of scale and the repurpose of existing offshore infrastructure, such as decommissioned oil and gas platforms. Additionally, the research highlights the impact of technological advancements on reducing production costs and improving efficiency. These insights are critical for investors, policymakers, and industry leaders aiming to assess the financial feasibility of offshore hydrogen projects.

4.1 Practical Implications and Recommendations

The findings from the literature review and metadata analysis offer guidance for industry stakeholders and project partners involved in offshore hydrogen production. The identification of key challenges, such as, ensuring constant supply of energy, energy storage optimization, and cost reduction, provides a roadmap for improving system design and operational efficiency. Industry stakeholders are encouraged to adopt modular system architectures and decentralized control strategies to enhance system scalability and reliability. Additionally, the integration of advanced forecasting models and optimization algorithms, can further improve system performance by dynamically adjusting to fluctuations in renewable energy generation and demand.

To enhance data collection and system evaluation, it is recommended that future projects prioritise the collection of high-resolution, real-time data from offshore installations. This will enable more accurate modelling and simulation of system dynamics, leading to better-informed design and optimization decisions. Furthermore, the development of standardized metrics for evaluating energy storage performance and system reliability will facilitate more consistent and comparable assessments across different projects and regions. Specific recommendations for system design include the adoption of HESS tailored to local renewable energy profiles and the use of advanced power electronics to optimize energy conversion processes.

4.2 Future Research Directions

Future research should focus on the integration of experimental data as it becomes available from pilot projects and operational offshore hydrogen production systems. This will allow for the validation and refinement of the metadata analysis and optimization algorithms developed in WP2. Additionally different defined geographical regions could provide further insights into the feasibility and performance of offshore hydrogen production under varying conditions.

Another promising direction is the integration of metadata analysis with the optimization algorithms developed in WP2. By incorporating real-time data and advanced forecasting models into the optimization process, it will be possible to achieve more dynamic and adaptive control of offshore hydrogen production systems. This integration could lead to significant improvements in system efficiency, reliability, and cost-effectiveness, tr advancing the transition to a sustainable energy future. Additionally, the potential for integrating metadata analysis with optimization algorithms presents the possibility for enhancing system performance and cost efficiency. By incorporating real-time forecasting models and adaptive control strategies, future studies can contribute to the development of more resilient and intelligent offshore hydrogen production systems.

To address challenges covered in this thesis, additional research in the field of regulatory and policies should be done. As the economic aspects set significant challenges to similar projects and regulations in the field remain unclear, a more direct approach to these issues would help frame what is possible currently and how things are expected to change in the future.

In conclusion, the findings from this research provide a solid foundation for advancing offshore hydrogen production technologies. By addressing the identified challenges and pursuing the recommended research directions, the project can make significant contributions to the development of efficient, reliable, and cost-effective offshore hydrogen production systems.

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