NATIONAL LABORATORY FOR
ENERGY AND GEOLOGY
RESEARCH FOR SUSTAINABILITY

HR EXCELLENCE IN RESEARCH
Desde 2013
HRS4R DE EXCELÊNCIA
EM RECURSOS HUMANOS
DE INVESTIGAÇÃO

Portugal Offshore Wind, Green Hydrogen, and Sustainable Fuels Power-to-X Pathways

Technical report
November 2025

Sofia G. Simões, Juan C. C. Portillo, Teresa Simões
Ana Estanqueiro, Justina Catarino, Paula Costa
Paula Oliveira, Paulo J. R. Pinto, Fernando Lopes
Tiago F. Lopes, António J. Gano, Margarida Fontes
Francisco Gírio

Title
Portugal Offshore Wind, Green Hydrogen, and Sustainable Fuels: Power-to-X Pathways

Authors
Sofia G. Simões, Juan C. C. Portillo, Teresa Simões, Ana Estanqueiro, Justina Catarino, Paula Costa, Paula Oliveira, Paulo J. R. Pinto, Fernando Lopes, Tiago F. Lopes, António J. Gano, Margarida Fontes, Francisco Gírio

Authors grouped by research unit
Sofia G. Simões, Juan C. C. Portillo, Paula Oliveira | LNEG – UER
Ana Estanqueiro, Teresa Simões, Justina Catarino, Fernando Lopes, Margarida Fontes | LNEG – UEREE
Francisco Gírio, Paula Costa, Tiago F. Lopes | LNEG – UBB
Paulo J. R. Pinto, António J. Gano | LNEG – UME

Address
LNEG – Laboratório Nacional de Energia e Geologia,
Estrada da Portela, Bairro do Zambujal
Apartado 7586 – Alfragide
2610-999 AMADORA, Portugal

Phone number
+351 210 924 600/1

ISBN
978-989-675-137-1

Release date
November 2025

Cite this document as:

S.G. Simões, J.C.C. Portillo, T. Simões, A. Estanqueiro, J. Catarino, P. Costa, P. Oliveira, P.J.R. Pinto, F. Lopes, T.F. Lopes, A.J. Gano, M. Fontes, F. Gírio, Portugal Offshore Wind, Green Hydrogen, and Sustainable Fuels: Power-to-X Pathways. Tech. rep., LNEG (2025). ISBN 978-989-675-137-1. URL `http://hdl.handle.net/10400.9/5864`.

Image of WindFloat Atlantic by Ocean Winds. Used with permission.

Executive Summary

Portugal has a vast coastal area and significant offshore wind resources. The country has set ambitious goals and identified areas for offshore wind auctions. In January 2025, the Portuguese government approved the Offshore Renewable Energy Zoning Plan (PAER), which is part of the National Energy and Climate Plan 2030 (PNEC 2030). The first auctions are expected to cover areas for the installation of an offshore wind capacity of 2 GW, with the medium-term goal of achieving 9.4 GW. This energy can be commercialised through various business models, such as selling electricity to the power grid, desalinating seawater, generating hydrogen, commercialising it in pure form, and/or using it to produce sustainable fuels for later trade.

The current Portuguese policy context is motivating investment in such projects. However, despite the rapid pace adopted by policymakers in creating incentives for offshore wind power investments, stimulating a Portuguese hydrogen economy and fostering low-carbon synthetic fuels requires further clarification of some issues for creating adequate conditions for investors. Thus, this report aims to assess the Power-to-X (P2X) possibilities in mainland Portugal up to 2035 to transform electricity from floating offshore wind power plants. The following pathways for P2X in Portugal were analysed: power to hydrogen, power to HVO (hydrotreated vegetable oil), power to methanol, power to ammonia and power to SAF (sustainable aviation fuels).

This report compiled information on the state-of-the-art strategies underway for offshore wind and green hydrogen in Portugal, introduced the P2X concept, discussed potential offshore wind P2X business models, described the main processes and technologies involved in P2X efforts, mapped potential consumers of green hydrogen and the supply chain of hydrogen and sustainable fuels, and investigated the techno-economics of P2X options considering a number of scenarios with the objective of identifying potential pathways for Portugal.

The following are the key general highlights.

- **Offshore floating wind** comprises a set of technologies still under development with small farms up to 100 MW, not yet in mainstream commercialisation, and the levelised cost of electricity from this source is higher than fixed-bottom deployments. In Portugal, the main areas identified for future public auctions are for offshore floating wind. The electricity costs would be transferred to any offshore wind P2X business model.

- The **load factor of green hydrogen production units**, i.e. the number of total operational hours in a year at equivalent rated power, is fundamental for the viability of any P2X strategy considering hydrogen as a commodity or feedstock for synfuels. The supply of electricity from complementary renewable sources onshore should also be considered to keep the load factor as close to 100% as possible. This additional electricity may come from the national electricity network or from a dedicated infrastructure through PPAs.

- The **weighted average cost of capital (WACC)**, or the total project discount rate, is critical for enabling potential businesses. This is related to the risk perception of investors and financing organisations; lower risk perception will enable a reduction in WACC and increase the willingness to invest and finance. In this sense, all stakeholders, including policymakers, must be concerned about derisking the sector.

- **Capital costs** are decisive for any P2X project development, and in this sense, sourcing of goods and services should allow CAPEX reduction. Technologies with the highest impact on CAPEX are those related to green hydrogen production (water electrolysis), CO_2 capture, and HVO and ammonia production. Targeting technology developments and industrialisation on these will aid in CAPEX reduction. Local supply chains with the right scales might be a competitive advantage for Portugal.

- An emerging **Portuguese supply chain** was identified with about 130 companies with activities that may act in the value chain of hydrogen and sustainable fuels, and also about 140 companies related to offshore wind and other renewables, a sector in which Portugal has historical competitive advantages. The country hosted pioneering projects in floating wind and wave energy motivated by its large offshore renewable energy resources.

- P2X projects involving green hydrogen and sustainable fuels are **OPEX**-intensive. This means that the derisking actions should pass by creating a favourable commercial environment for businesses in all the value and supply chains related to the P2X business models. More than 75% of the LCOH or LCOX comes from total operational expenditures, i.e. electricity, fixed O&M costs, and water (named in importance order).

This study considered the techno-economic analysis of the following offshore wind P2X options: i) the Production and storage of hydrogen in gas form, ii) its liquefaction and storage in liquid form, iii) the production and storage of ammonia, iv) the production and storage of methanol, v) production and storage of biodiesel from HVO, and vi) production and storage of SAF. Also, the distribution of the different products (commodities) was considered.

The methodology of the techno-economic analysis involved the selection of one of the offshore planned areas for offshore wind in Portugal, and, based on the location of the area and its potential installed capacity, both the location onshore and the capacity of the hydrogen and sustainable fuels hub were determined. The selected location is the offshore planned area of Leixões, with a potential offshore wind farm capacity of 1 GW, which is expected to be operational by 2035. The capacity of the hydrogen production unit was assumed to be 500 MW starting operations in the same year, and all the electricity generated from the offshore wind would be dedicated to operating the hydrogen and sustainable fuels hub. The quantities of sustainable fuel production and their distribution depend on the definition of seven scenarios. The techno-economic parameters for the evaluation and comparison of scenarios are presented in this report. The analysis provided useful information for stakeholders in both the private and public sectors.

The gaseous hydrogen distribution was considered to be via the European Hydrogen Backbone from Portugal to Germany. The distribution of liquid hydrogen and other sustainable fuels was considered to be via maritime transport. The levelised cost of hydrogen (LCOH) and X (LCOX) were the main indicators for comparing the different offshore wind P2X scenarios in this study. The main findings are the following:

- **HVO production stood out among the offshore wind P2X options studied.** The LCOX for HVO was found to be between 63 and 110 €/MWh, an interval which is lower than the average price of diesel in continental Portugal and Europe during the year 2024, about 158 and 172 €/MWh, respectively.

- **Ammonia could become competitive with other green ammonia supplies** from other places in the world due to its low LCOE, which is **most probably achievable when the electricity source is from renewables onshore**. However, it presents higher costs than grey ammonia.
- **Methanol, SAF, and liquefied hydrogen resulted in higher LCOX and LCOH within the scenarios analysed**. More innovation efforts are recommended to enhance efficiency in conversion, storage, and distribution processes, thereby reducing costs.
- **Hydrogen production and storage in gas form can decrease costs to less than 5 €/kg** for low LCOE (i.e., low cost of electricity), which remains a challenge for floating offshore wind in the next decade. Instead, **with onshore renewable electricity**, it may be a cost-effective option to produce green hydrogen at lower costs.

The following recommendations are drawn for policy making:

- **Efforts should be directed towards the development up to market readiness level of technologies related to hydrogen production and the production, storage, and distribution of sustainable fuels**. Support for technology R&D and innovation, and industrialisation of national production is of utmost importance to reduce CAPEX. Emphasis should be placed in promoting the development and strengthening of Portuguese industrial value chains in these domains.
- However, actions should not only be directed to support CAPEX reductions; in fact, the most important share of the costs of a P2X project is associated with the operation and maintenance expenses (OPEX). **Substantial efforts should be directed to enable the reduction of costs during the operating lifetime of the hydrogen and sustainable fuels businesses**. **Fiscal incentives that cover the entire lifetime of the projects could be considered, especially for pilot, demonstration, and the first large scale projects.**
- But also, **incentives might also be key to aid CAPEX reduction**. This could be achieved by **creating favourable conditions for the entire supply chain of goods and services associated with P2X projects**, especially for pilot, demonstration, and the first large projects.
- **A clear regulatory framework to enable agile licensing processes is fundamental** to reducing bottlenecks and derisking offshore wind and P2X projects.

Portugal's strategic approach to offshore wind and P2X technologies positions the country as a frontrunner in the decarbonisation of the economy. By leveraging its extensive coastal resources and fostering a supportive policy environment, Portugal is set to transform its energy landscape and drive sustainable economic growth. This report provides a comprehensive analysis to guide stakeholders in realising the full potential of these initiatives.

Contents

List of Figures

List of Tables

Nomenclature

AC	Alternating Current
AD	Adsorption Desalination
AEC	Anion-Exchange Cells
AHP	Annual Hydrogen Production
AHP_{nom}	Annual nominal hydrogen production - as specified by manufacturer
AML	Lisbon Metropolitan Area
AMM	Ammonia
ANTRAM	National Association of Public Road Freight Transporters
ASTM	American Society for Testing and Materials
bp	Boiling Point
CAPEX	Capital Expenditures
CDI	Capacitive Deionization
COD	Commercial Operation Date
CrIEM	Crystallizer with Ion Exchange Membrane
CRM	Critical Raw Material
DAC	Direct Air Capture
DC	Direct Current
DECEX	Decommissioning Expenditures
DGEG	General Directorate of Energy and Geology
ED	Electrodialysis
ENH2	Portuguese National Hydrogen Strategy
ENTSO-E	European Network of Transmission System Operators for Electricity
EPC	Engineering, Procurement and Construction
EPRI	Electric Power Research Institute (USA)
EU	European Union
FID	Final Investment Decision
FO	Forward Osmosis
FT	Fischer-Tropsch process
GFL	Grid Following
GFM	Grid Forming
GH2	Hydrogen Gas
GHG	Greenhouse Gas
H_2	Hydrogen
HEFA	Hydro-processed Esters and Fatty Acids
HPP	High pressure pumps
HRS	Hydrogen Refuelling Station
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
HVO	Hydrotreated Vegetable Oil
IBRs	Inverter-Based Resources
IEA	International Energy Agency

IEC	International Electrotechnical Commission
IPPC	Integrated Pollution and Prevention Control
IRENA	International Renewable Energy Agency
LCOH	Levelised Cost of Hydrogen
LCOX	Levelised Cost of ”X” product
LF	Water electrolysis plant Load Factor
LH2	Liquefied Hydrogen
LPG	Liquefied Petroleum Gas
LULUCF	Land Use, Land Use Change and Forestry
MD	Membrane Distillation
MED	Multi-effect Distillation
MET	Methanol
MON	Motor Octane Number
MSF	Multistage Flash Distillation
MVC	Mechanical Vapour Compression
NECP	National Energy and Climate Plan
NEPS	Net Energy Production
NREL	National Renewable Energy Laboratory (USA)
O&M	Operation and Maintenance
OEM	Original Equipment Manufacturers
OPEX	Operational Expenditures
$\mathrm{OPEX}_{\mathrm{fix}}$	Annual Fixed Operational Expenditures
$\mathrm{OPEX}_{\mathrm{var}}$	Annual Variable Operational Expenditures
OWF	Offshore Wind Farm
OWPP	Offshore Wind Power Plant
P2X	Power-to-X
PAER	Offshore Renewable Energy Zoning
pe	Population Equivalent
PLL	Phased-Locked-Loop
PPA	Power-Purchase Agreements
PRO	Pressure Retarded Osmosis
PRTR	Pollutant Release and Transfer Register
R&D	Research and Development
RE	Renewable Energy
RED	Renewable Energy Directive
RES	Renewable Energy Sources
RFNBO	Renewable Fuel of Non-Biological Origin
RNC2050	Portuguese Carbon Neutrality Roadmap 2050
RNTG	National Gas Transport Network
RO	Reverse Osmosis
RON	Research Octane Number
RWGS	Reverse Water-Gas Shift-reaction
SAF	Sustainable Aviation Fuel
SEC	Specific Energy Consumption
SNG	National Gas System

SOFC	Solid Oxide Fuel Cells
SW	Sea Water
TBT	Top Brine Temperature
TRL	Technology Readiness Level
TVC	Thermal Vapour Compression
VC	Vapour Compression
WACC	Weighted Average Cost of Capital
WTG	Wind Turbine Generator
WWTP	Wastewater Treatment Plant
n	Year n
n_{lifetime}	Last year of operation of the assets, i.e., end of lifetime year
r	Annual discount rate
$r_{\text{degradation}}$	Annual rate of degradation

1 Setting the scene

This report presents an overview of the Portuguese context regarding Power-to-X approaches based on off-grid offshore wind projects in the country.

Portugal has a vast coastal area and extensive offshore wind resources, allowing for important quantities of electricity to be generated in the future. This power can be commercialised via varied business models, such as selling electricity to the power grid, desalinating seawater, generating hydrogen, commercialised in a pure form and/or used for producing synthetic fuels for their later trade.

The current Portuguese policy context is motivating for investment in such projects. Nonetheless, despite the rapid pace adopted by policymakers towards creating incentives for offshore wind power investments, stimulating a Portuguese hydrogen economy and fostering low-carbon synthetic fuels requires further clarification of some issues for creating adequate conditions for investors. Thus, this report aims to assess the Power-to-X possibilities in mainland Portugal up to 2030 for transforming electricity from floating offshore wind power plants.

1.1 Clean energy transition and Power-to-X

1.1.1 In the European Union

The current European Union (EU) policy landscape is geared towards **carbon neutrality by 2050** to comply with the 1.5°C temperature increase target as in the Paris Agreement. There is an intermediate 2030 target of less than 55% greenhouse gas (GHG) emissions compared to 1990 levels, and both targets are enshrined in the July 2021 EU Climate Law [27].

Against this background, the overarching **EU Green Deal** sets a roadmap to achieve the climate targets and to "transform the EU into a modern, resource-efficient and competitive economy" [28]. A substantial part of the effort is allocated to the so-called "clean energy transition", which includes developing a power sector based largely on renewable energy sources (RES), along with improving energy efficiency, ensuring secure and affordable energy and a more integrated, interconnected and digitalised EU energy market.

Correspondingly, the **policy arena is evolving at an unprecedented pace**, with a set of legislation reviews and updates to deliver the more ambitious mitigation target, as orchestrated within the July 2021 **'Fit for 55' package** [29]. In May 2022, the **REPowerEU Plan**, created as a response to the impacts on the EU energy system due to the war in Ukraine, sets the actions to diversify the EU's (natural gas) energy supply to save energy and, more importantly, for this report, to establish the investment framework in renewable energy. In March 2023, the EU provisionally agreed on an increased ambition for the **Renewable Energy Directive** (RED) 2030 target from 32% to 42.5% RES in the EU's overall energy mix [30]. The revised **Directive EU/2023/2413** entered into force on 20 November 2023. The deadline for EU Member States to transpose the revised Renewable Energy Directive (RED III) into national law was 21 May 2025.

The RES target includes RES electricity, RES heating and cooling and RES transport fuels, such as hydrogen, methanol, methane, ethanol, hydrotreated vegetable oil (HVO), or ammonia, among others. **This report focuses on RES electricity produced from offshore wind power plants and its subsequent uses**, with special emphasis on hydrogen production via water electrolysis. Therefore, it is noteworthy to highlight both the 2020 EU strategy for offshore renewable energy [31] and the EU hydrogen strategy [32] (also from 2020).

The **EU hydrogen strategy** identifies policy actions to implement an EU hydrogen economy along the following areas: (i) investment support; (ii) support production and demand; (iii) creating a hydrogen market and infrastructure; (iv) research and cooperation; and (v) international cooperation. The hydrogen strategy promotes hydrogen and hydrogen-derived synthetic fuels, always based on carbon-neutral CO_2. Until 2024, it aimed to deploy at least 6 GW of RES hydrogen electrolysers in the EU, producing up to 1 Mt of RES hydrogen. By 2030, these goals increase to 40 GW of electrolysers and 10 Mt of RES hydrogen. The subsequent REPowerEU plan further increased the 2030 ambition, not only to produce 10 Mt of RES H_2 in the EU but also to import an additional 10 Mt. To do so, a 'hydrogen accelerator' has been devised, as well as the European Hydrogen Bank, among other initiatives.

The EU strategy on offshore energy addresses both offshore wind and ocean energy. It sets forward actions to foster their long-term sustainable development and targets for an installed capacity of at least 60 GW of offshore wind by 2030 and 300 GW by 2050 (in 2021, the EU capacity was approximately 14.6 GW). The deployment of offshore wind energy is acknowledged as "at the core of delivering the European Green Deal" [33] across the five EU sea basins (the Atlantic Ocean and the North, Baltic, Mediterranean, and Black seas). Achieving these targets requires the supported development of energy technologies and infrastructure, a regulatory framework, and market designs addressing objectives in national maritime spatial plans.

Across all policy areas addressing the clean energy transition, developing and strengthening an **EU-based resilient technology supply chain is seen as a key priority** to ensure the ambitious targets are achieved and to foster job creation and economic development.

1.1.2 In Portugal

Portugal aims to be **carbon neutral by 2050** as per its 2019 Carbon Neutrality Roadmap 2050 (RNC2050) [34] and to cut its 2030 GHG emissions by -45%/-55% compared to 2005 values, as in the 2020 National Energy and Climate Plan (NECP) [35]. The 2021 Portuguese Climate Law [36] not only defined the framework for national climate policy in its various dimensions but also **updated the 2030 national GHG mitigation target to -55%**. It also set a GHG mitigation target for 2040 (-65% to -75% from 2005 values). The 2050 carbon neutrality goal is maintained, but its anticipation to no later than 2045 will be assessed (until 2025). These GHG targets do not consider land use, land use change, and forestry (LULUCF) and thus refer to cuts in GHG emissions from energy production and consumption and industrial processes. Therefore, the 2050 carbon neutrality target corresponds to reducing circa -90% GHG energy and processes emissions from 2005 values.

The NECP initially set a **national RES 2030 target** of 47%, disaggregated into 80% RES electricity, 38% RES heating and cooling and 20% RES consumption in the transport sector. The Decree-Law No. 84/2022 [37] updated the global 2030 RES target and increased to 49% the national RES 2030 target, and the RES transport target to 29%. The second revision of the

NECP 2030 was approved in April 2025 by the Portuguese Parliament [38], updating the national RES 2030 target to 51%. According to RNC2050, reaching carbon neutrality will require, in 2050, 100% RES electricity, 66% to 68% RES heating and cooling in buildings, and 96% to 94% RES in transportation. The draft revised NECP [39], presented in June 2023, aimed for 85% RES electricity[1], 47% RES in heating and cooling, and 23% RES in transportation by 2030. By the end of 2021, these values were 58.43% for RES electricity, 42.68% for RES heating and cooling, and 8.61% for transportation, which combine to 33.98% for the overall RES target [40].

Zooming in on **RES electricity and offshore wind power**, Portugal has set ambitious goals as can be seen in Table 1.1. Between the first version of the NECP, the RNC2050, and the recent draft NECP revision, the targets for RES installed capacity have increased. This is due to EU policy developments, such as 'Fit for 55' and REPowerEU, improvements in power plant technology, the anticipated increase in Portuguese industry activity, and the growth of hydrogen production using electrolysis and renewable energy sources (RES) power.

Table 1.1: Overview of Portuguese RES power installed capacity targets for 2030 and 2050 (in GW)[1]

Power technologies	2022	2030 NECP	2030 revised NECP (2023)	2030 2nd revision NECP (2024)	2050 (RNC2050)
Hydropower (no PS[2])	8.13	4.6	4.2	4.2	5.1
Hydropower (PS)	8.13	3.6	3.9	3.9	3.4
Onshore wind	5.67	9	10.4	10.4	12
Offshore wind	0.02	0.3	2	2	0.2
Solar PV[3] utility size	1.5	7	14.9	15.1	14.4
Solar PV roof	1.07	2	5.5	5.7	0.2
CSP[4]	0	0.3	0.6	0.6	0
Biomass	0.19	0.5	1.4	1.3	1.8
Other RES[5]	0.09	0.1	1.4	-	1.8
Geothermal	0.03	0.06	0.1	0.1	0
Waves	0	0.07	0.2	0.2	0
Total	**8.57**	**22.90**	**39.00**	**39.00**	**32.00**

[1] 2022 values from DGEG Portuguese Directorate General for Energy and Geology. 2030 NECP values retrieved from [35]. 2030 draft NECP revision retrieved from [39]. 2030 updated NECP second revision retrieved from [38, 41]. 2050 values retrieved from [34] for the more conservative scenario.

[2] Pumped Storage

[3] Photovoltaic

[4] Concentrated Solar Power

[5] Other RES refers to biogas & waste

The Portuguese target for 2030 offshore wind power installed capacity has evolved from 0.3 GW to 2.0 GW, departing from the currently installed 0.02 GW. It should be mentioned that the technical potential for offshore wind power is substantially higher, with estimated values of 38 GW [42], detailed further in this report.

Offshore wind policy development in Portugal was especially active in 2023. The revised draft of the NECP mentions the intention to start a phased auction process, with a view to allocating, by 2030, permits for 10 GW offshore power plants. This number has been revised

---

[1] It does not consider the consumption of electricity for the production of hydrogen, as a European methodology for this has not yet been defined within the scope of the SHARES tool from EUROSTAT.

to 9.4 GW in the most recent NECP. These plants will mostly be deployed after 2030. These and other aspects have been made public in July 2023 with the publication of the conclusions of the Portuguese Offshore Wind Working Group [43]. The group was created by the government in the Dispatch no. 11404/2022, of 23 September [44] and included government representatives (from marine, energy and climate and infrastructure cabinets), from the Marine (DGRM) and Energy & Geology (DGEG) Directorates, from the National Energy and Geology Laboratory (LNEG), the Energy Services Regulators (ERSE), the transmission power system operator (REN), the Association of Portuguese Renewable Energy Companies (APREN) and of the Portuguese Ports Association (APP). The group had the mandate to:

- Propose **areas for deployment** of maritime RES power plants, with an indication of the interconnection points to the national transmission power grid within the scope of the national maritime spatial planning Situation Plan (PSOEM). Preferential areas should be identified;
- Propose a **timeline for deployment in the abovementioned areas**, including capacity volumes to be assigned, towards launching competitive procedures for allocation of (i) capacity reserve titles (known in Portugal as TRC) for the injection in the public service power grid (RESP) and (ii) 'permits of private use of the maritime space' (known as TUPEM);
- Propose a **model for assigning both TRC and TUPEM** based on an international benchmarking exercise;
- Propose the **technical and investment model for the development of the required power infrastructure** (offshore and onshore) considering both the proposed deployment timeline and the increased demand for RES electricity due to foreseen industry investments, namely for the production of hydrogen and its derivatives;
- Assess the **needs for the development of port infrastructure**, both for the construction of power plants and for the development of an offshore RES national industrial value chain.

All the objectives have been addressed in the Working Group report. Regarding areas, it was proposed that, in the first phase, a capacity of up to 3.5 GW should be made available in the areas of Viana do Castelo, Leixões and Figueira da Foz, subject to one or more competitive procedures. As mentioned in the revised NECP, the capacity should be allocated through auctions in subsequent phases until a total of about 9.4 GW. An expression of interest call was launched during the second semester of 2023, in which 50 companies expressed interest in participating in the dialogue that precedes the competitive procedures. The first competitive procedure is still waiting for further details. It is estimated to open by the end of 2025 or the beginning of 2026, starting with a pre-qualification phase that will last no less than three months. These aspects are detailed further ahead in this report.

Regarding the EU case, it is worthwhile to mention the **Portuguese hydrogen policies**. The 2020 National Hydrogen Strategy (ENH2) [45] sets public policies to promote an industrial policy along the whole hydrogen value chain. Only RES hydrogen is considered, with special emphasis on water electrolysis. ENH2 brings forward a set of initiatives to trigger the required private investment toward a Portuguese hydrogen economy, namely, (i) regulation of the production of RES gases; (ii) regulation of the injection of RES gases into the national natural gas network; (iii) mechanisms to support hydrogen production; (iv) implementing guarantees of origin for RES gases; (v) ensuring that financial resources are available. The strategy sets several binding targets by 2030: 15% hydrogen injection into the natural gas grid, 5% of hydrogen in the final energy consumption, and 5% of hydrogen in final energy consumption in road transport and industry. Finally, the ENH2 set the **target to install up to 2.5 GW of electrolysers for green hydrogen production by 2030. In the most recent revision of the NECP, this target is projected to be 3 GW by 2030; given the slowdown and shelving of some projects**, the target was reduced from the initial 5.5 GW in the first revision to 3 GW, as considered in the latest revision.

1.2 Structure of this report

This report is in six main sections. The first provides a context for the clean energy transition and Power-to-X (P2X) framework in Europe and Portugal. The second introduces the offshore Power-to-X concept and provides information about the offshore wind sector in Portugal. The third section focuses on potential business models for Portugal, technologies, and processes associated with offshore Power-to-X. The fourth section presents information on current hydrogen projects, potential consumers, and the supply chain in Portugal. The fifth section introduces the methodology and results obtained for the techno-economic analysis of different P2X options. Finally, Section 6 draws conclusions and recommendations.

2 Introducing offshore wind Power-to-X

This section introduces the concept of Power-to-X and the offshore wind strategy and resource for Portugal.

2.1 Power-to-X

Power-to-X, also known as PtX or P2X refers to a portfolio of energy conversion technologies that use electricity to produce chemicals or energy carriers, namely:

- Hydrogen;
- Methane or synthetic natural gas;
- Synthetic liquid fuels (also known as e-fuels or sustainable fuels), such as methanol, ammonia, synthetic diesel, kerosene, or jet fuel (aviation fuel).

In the common use of the term, **P2X is associated with renewable and/or carbon-neutral fuels** since it is mainly driven by the urgent need to decarbonise energy systems across the globe. Thus, in this context, “power” refers to renewably sourced electricity which is then converted to “X”, i.e. either a substance or one of the previously mentioned energy carriers. Green hydrogen is one of the “X” products, which can be subsequently converted into other sustainable fuels, like the ones previously mentioned.

P2X approaches are emerging as interesting due to the following:

- Allow for long-term storage of surplus renewable electricity (in the form of “X”);
- Allow for the replacement of fossil fuels with carbon-neutral ones, especially in sectors “hard-to-abate”;
- Contribute to GHG emission mitigation via reduction of CO_2 emissions;
- Facilitate coupling of electricity with heating/cooling and with transportation;

Moreover, most P2X alternatives are currently geared for future scalability [46], especially if offshore wind energy is the source of “power” due to offshore wind power plants’ large potential capacity and outputs.

2.2 Offshore wind power in Portugal

Portugal has become a leading EU country in the development of onshore wind energy and since 2019, also (floating) offshore wind. In fact, in 2019, the Portuguese Atlantic Coast became home to the second floating wind farm in Europe and the first offshore wind power plant in Portugal, namely the WindFloat Atlantic project [47]. WindFloat Atlantic is located 18 km away from the coast with a water depth of approximately 100 m, with a capacity of circa 25 MW in floating wind power. It has three 8.4 MW wind turbines supplying electricity to 25000 Portuguese households per year [47]. WindFloat Atlantic is the world’s first semi-submersible floating offshore wind farm.

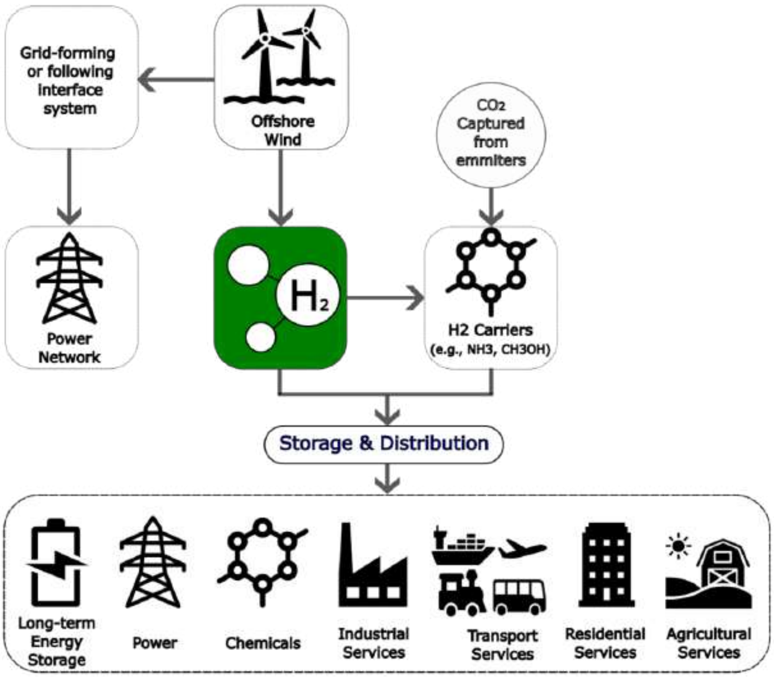


Figure 2.1: Overview of P2X options from offshore wind power. Source: LNEG.

This cutting-edge feat has captured the attention of many other coastal countries hoping to develop similar technology. Regarding offshore wind resources, in 2018, the most up-to-date high-resolution offshore wind potential Atlas was made available for Portugal. This offshore wind atlas is developed with a sophisticated atmospheric mesoscale model, coupled with a 4D-VAR data assimilation technique and ingests several sources of oceanic available data to produce the most state-of-the-art high-resolution long-term offshore wind atlas, computed for heights greater than 100 m, according actual and future turbine technology needs [48–50].

Figure 2.2 maps the number of hours at full capacity in Portugal for a typical 8.4 MW offshore nominal power at a height of 140 m above sea level. Considering as a minimum threshold, annual operating hours at full capacity are 3200 h/year for fixed offshore wind and 3500 h/year for floating offshore, which represent capacity factors of about 0.36 and 0.40, respectively. Substantial maritime areas are expected to be above this threshold, especially in the northwest, with around 4000 up to 4500 h/year (i.e., capacity factors between 0.46 and 0.52).

Figure 2.3 maps the offshore capacity factor map computed for a height of 100 m above sea level. The map is retrieved from the Publicly Global Wind Atlas, where the capacity factor is based on a typical Class II offshore wind turbine. In this figure, the European countries are depicted. According to this Map, European countries like the United Kingdom, Ireland, Denmark, the Netherlands, Germany, and Balkan countries show capacity factors above 0.5 up to 0.6, while for Portugal, values range between 0.4 and 0.5+, which makes Portugal a good player for developing offshore wind projects. The highest values for Portugal are mainly located in the North-westwards and westwards of continental Portugal.

Considering the availability of wind resources and the socio-economic characteristics of the country, offshore wind presents a great potential to drive a resurgence in the Portuguese naval, metal and engineering sectors (among others). However, up to 2019, the country maintained a restrictive approach to offshore wind farm development due to opposition from maritime sectors and environmental actors on the delimitation of sea areas and concerns with undetermined noise impacts on tourism activities along the Portuguese coastal areas.

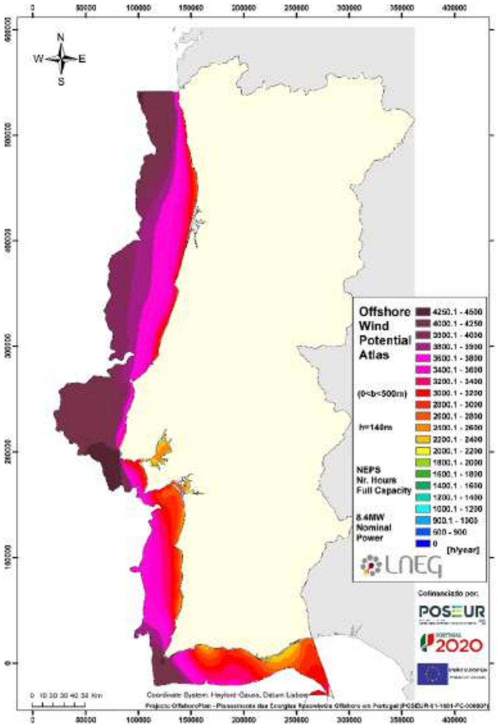


Figure 2.2: Map of the number of hours at full capacity calculated for the height of 140 m above sea level for Continental Portugal, obtained with a typical offshore wind turbine model with 8.4 MW nominal power. The energy resource is plotted between coastal line and bathymetry of up to 500 m depth.

Therefore, it is necessary to identify not only the maritime areas with adequate wind resources but also with no conflicting use/restrictions. These include aquaculture, nature protection, fishing, navigation, military interest, or having a high visual impact perceived from the mainland.

A recent study estimated the Portuguese technical offshore wind power potential by identifying the maritime areas that simultaneously have i) adequate wind power resources, ii) no maritime use constraints, and iii) adequate bathymetry [42]. The analysis was made for both floating and fixed (shallow water technology) wind power plants. Figure 2.4 illustrates the resulting areas where maritime use restrictions are depicted in grey. In green are shown the areas with technical potential for offshore wind (good wind resources and adequate bathymetry) where floating or fixed power plants can potentially be deployed. It is estimated a total technical offshore wind power potential capacity of up to 38 GW, of which 36 GW are for floating and the remaining 2 GW exclusively for shallow water technology [42]. The actual deployment of this capacity depends on permitting and market willingness to invest.

Subsequently, whereas in most EU member states, offshore wind power is limited to shallow waters [51], in Portugal, floating wind power developments will potentially steer and consolidate the country as one of the leading countries in the world in floating offshore wind energy.

As mentioned in the previous section, Portugal's current ambition is to auction permits for 10 GW of installed offshore floating capacity. The first floating offshore wind auction is expected to start by the end of 2025 or the beginning of 2026. The preliminary areas for deployment were published in 2023 [43]. The final Offshore Renewable Energy Zoning Plan (PAER) was approved by the Portuguese government in January 2025. This plan is an integral part of the National Energy and Climate Plan 2030 (NECP 2030) and aims to promote the exploration of Portugal's ocean areas for offshore renewable energy production. The PAER designates specific maritime zones for the development of commercial offshore wind energy projects (Resolution of the Council of Ministers No. 19/2025, dated February 7, 2025, and Rectification Declaration No. 18-C/2025/1, dated April 8, 2025).

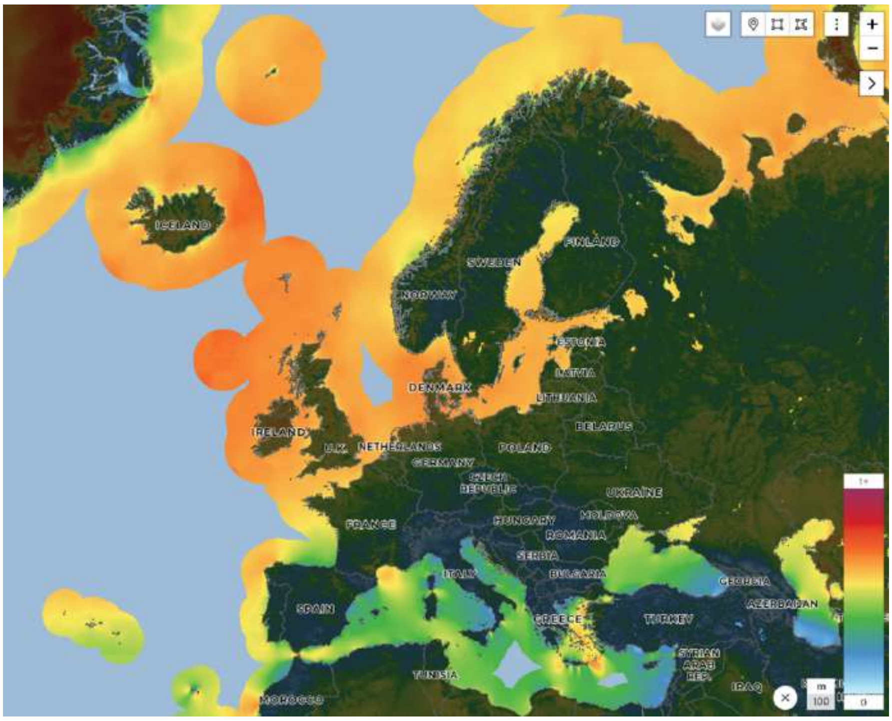
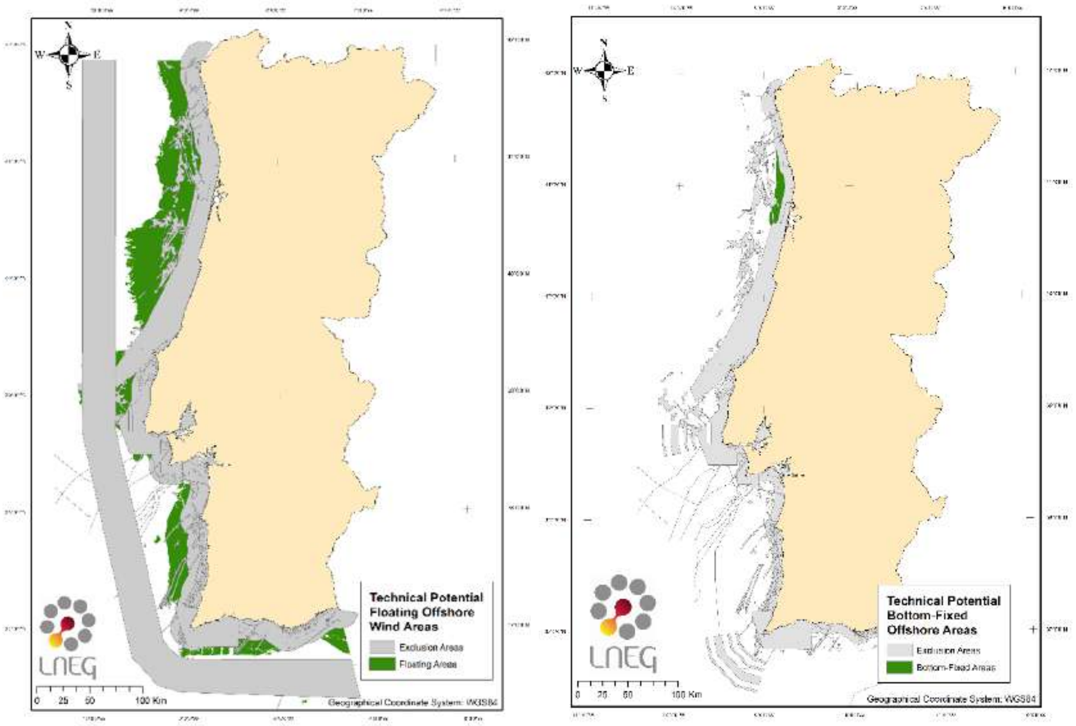


Figure 2.3: European Wind Offshore Capacity Factor Map for h=100m - Typical IEC class II offshore wind turbine (values between 0 and 1), multiply by 8760 to obtain NEPS. Source: Global Wind Atlas (`https://globalwindatlas.info/en`).

The areas cover a maritime surface of about 2700 km^2 with a potential installed capacity of 9.4 GW. The areas are depicted in Figure 2.5 [1]. They are distributed through the western coast of Portugal, where the bathymetry varies between 100 m to 500 m depth. In these areas, the offshore energy resource (for a height of 140m above sea level) is high above 4000 h/year. Northern and Western areas have higher offshore wind potential, with values greater than 4200 h/year, except for the West-southern areas, where the offshore wind resource is even higher, with values ranging between 4200 to 4500 h/year. Figure 2.5 shows the areas identified for offshore wind deployments in Portugal.



(a) (b)

Figure 2.4: Maritime space use restrictions and wind offshore technical potential for (a) floating and (b) shallow water technology. Source: LNEG.

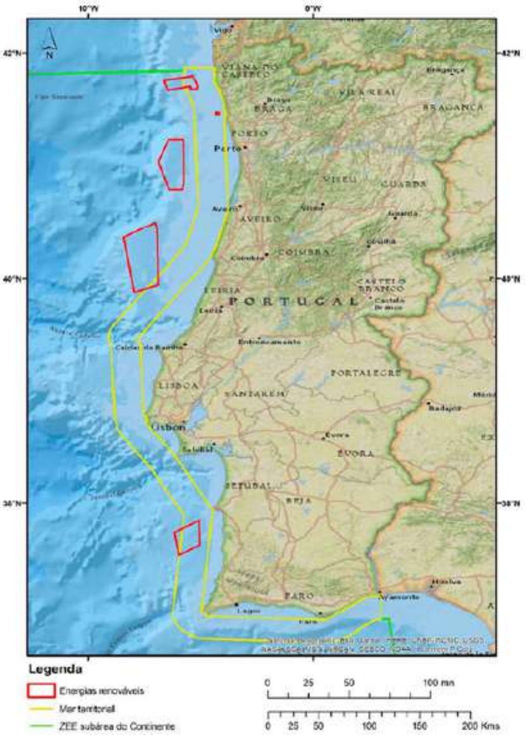


Figure 2.5: Areas for the deployment of offshore wind power in Portugal [1].

3 Offshore wind P2X business models in Portugal

This section presents an overview of potential business models for Portugal and describes the main technologies and processes associated with offshore wind, hydrogen production, and sustainable fuel production.

3.1 P2X business models

The following P2X business models departing from offshore wind are addressed in this report:

1. Power-to-power or P2P, where electricity is sold to power grid.
2. Power-to-desalination, where electricity is supplied directly to desalination plants. Water scarcity is becoming an important issue in certain regions, and desalination plants might aid in mitigating water shortfall risks and satisfy water needs for hydrogen production in Portugal.
3. Power-to-hydrogen, where hydrogen is sold for national consumption (in Portugal):
    - as fuel to Portuguese industry.
    - as raw material for the Portuguese chemical industry.
    - as fuel for transport services.
    - blending into the national gas network.
4. Power-to-hydrogen, where hydrogen is exported:
    - via the CELZA pipeline.
    - as ammonia via shipping from the Port of Sines.
5. Power-to-synthetic fuels where hydrogen is used to produce:
    - Hydrotreated vegetable oil (HVO).
    - Methanol.
    - Ammonia.
    - Sustainable aviation fuels (SAFs) and other synthetic fuels.

A schematic representation of the considered P2X business models for Portugal is presented in Figure 3.1.

3.2 Relevant offshore P2X technologies for Portugal

The following technologies are considered relevant for offshore wind P2X in Portugal. Table 3.1 presents some selected technologies, their estimated technology readiness level (TRL), and the value chain step or component to which they are deemed to belong within the whole value chain of offshore wind Power-to-X.

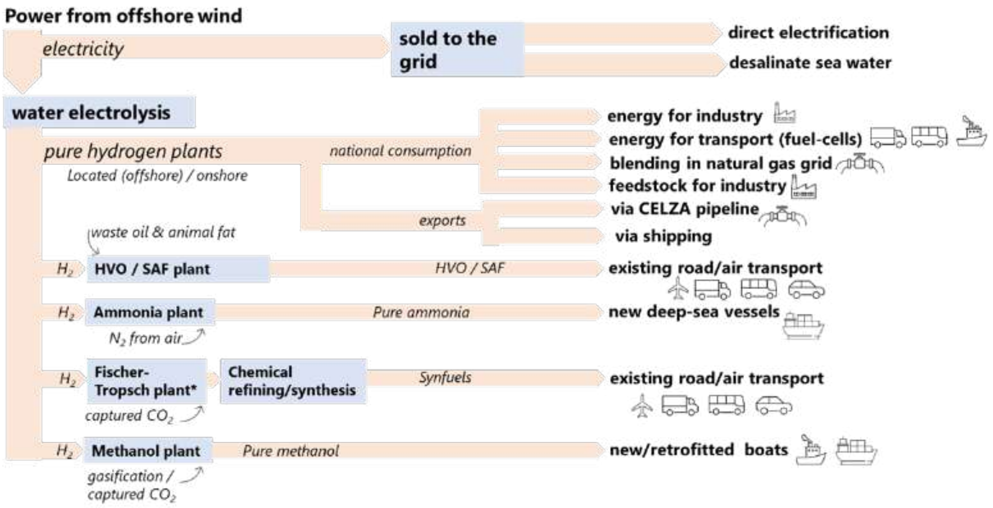


Figure 3.1: Offshore P2X business models considered for Portugal. * Fischer-Tropsch plants are not perceived as highly relevant in the medium term. Source: LNEG.

3.2.1 Floating offshore wind power plants

Floating offshore wind projects have been gaining momentum over the last decade, despite the slowdown period of the last two years. They represent a way to leverage the stronger wind offshore at deeper locations. As the shallower locations adequate for fixed-bottom wind projects are becoming scarcer, the possibility of going further from the coast and to locations that were not possible before is turning into reality. As described before, Portugal has been one of the pioneers in demonstrating offshore wind technologies, and there is currently a three-floating wind turbine park, the WindFloat Atlantic, which has survived very harsh environmental conditions over the last four years. Several developers are engaging in floating wind projects around the world with a few technologies that have reached advanced TRLs, like the WindFloat, Hywind, Floatgen, Tetra-Spar, and DemoSATH, just to name some of them. These concepts have had at least full-scale demonstrators, with the first three being the most considered for future commercial projects. However, there are a series of other concepts that are under development with lower TRLs, which might become of interest to developers and investors in the future.

Regarding capacity factors, floating offshore wind turbines have shown higher capacity factors when compared with onshore wind deployments. The capacity factors of deployments offshore could reach values considerably higher than 0.5 (see Section 2.2 for more details about expected values for Portugal).

NREL (2022) estimated floating offshore wind projects' levelised cost of energy (LCOE) at about 145 US$/MWh (about 138 €/MWh considering an average exchange rate in 2022, which might represent about 147 $€_{2025}$/MWh considering an average inflation rate of 3% and current exchange rates from US$ to €) for a case study in the USA [52]. The capital expenditures (CAPEX) were estimated for the case presented in about 6169 US$/kW installed (about 5870 €/kW), representing about 82% of the total LCOE. Operational expenditures (OPEX) were, for the same case, 87 US$/kW/year (about 82.8 €/kW/year), representing about 18% of the LCOE. Another study has estimated the LCOE of floating wind plants for Portugal in the order of 125 €/MWh for a 1 GW offshore wind farm comprised of 100 turbines of 10 MW each [53]. Total CAPEX was estimated in the order of 3000 €/kW installed, representing about 79% of the

LCOE. Regarding the OPEX, it was considered to be about 90 €/kW/year, representing 21% of the LCOE. DNV (2024) estimated that the LCOE for floating offshore wind may decrease up to 65 €/MWh by 2050 driven mainly by the economies of scale (i.e., volume increase), standardisation and the learning [54].

Table 3.1: Overview of relevant offshore wind P2X technologies for Portugal (adapted from [11]).

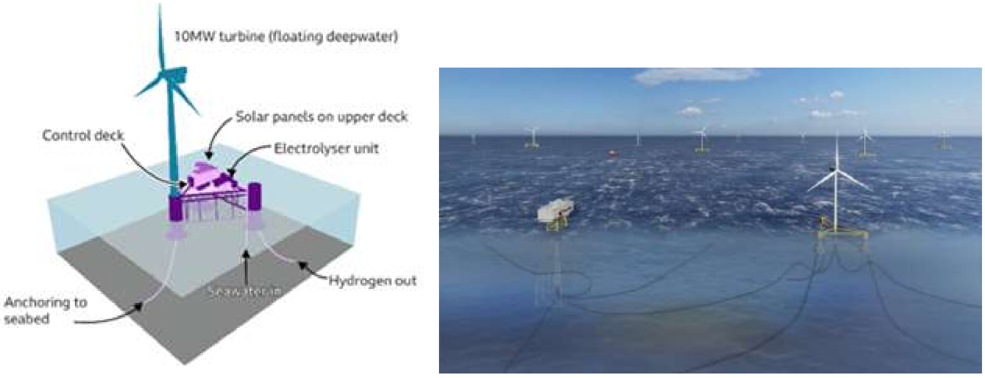
Technology	**Technology Readiness Level (TRL)**	**(Global) Value Chain Step**
Floating offshore wind power plants	5-9	Production
Alkaline Electrolysis Cells (AEC)	9	Production
Solid Oxide Electrolysis Cell (SOEC)	7-8	Production
Proton Exchange Membrane (PEM)	9	Production
Methane synthesis	8-9	Production
Methanol synthesis	8-9	Production
DME (dimethyl ether) synthesis	3-9	Production
Fisher-Tropsch synthesis (FTS)	5-9	Production
Ammonia synthesis through Haber-Bosch process	9	Production
Ammonia synthesis through electrocatalytic nitrogen reduction reaction	4-6	Production
Hydrogen compression	9	Infrastructure
New hydrogen pipelines	9	Infrastructure
Retrofitting of natural gas pipelines to hydrogen	9	Infrastructure
Road and rail transportation of gaseous and liquid hydrogen	9	Infrastructure
Hydrogen shipping	6-8	Infrastructure
Hydrogen geological storage	7-8	Infrastructure
Hydrogen storage tanks	9	Infrastructure
Liquid electro-fuels shipping	7-8	Infrastructure
Solid Oxide Fuel Cell (SOFC)	8-9	Demand
Proton Exchange Membrane (PEM) Fuel Cell	9	Demand
Molten Carbonate Fuel Cell (MCFC)	9	Demand
Phosphoric Acid Fuel Cell (PAFC)	8-9	Demand
Ammonia Fuel Cell (DAFC)	7	Demand
Direct Methanol Fuel Cell (DMFC)	6-7	Demand
2-stroke methanol dual fuel engine for marine transportation	7-8	Demand
Retrofitting of 2-stroke engines for marine transportation to methanol	7-8	Demand
2-stroke ammonia dual fuel engine for marine transportation	7-8	Demand
4-stroke ammonia dual fuel engine for marine transportation	7-8	Demand
Retrofitting of 2 and 4-stroke engines for marine transportation to ammonia	7-8	Demand
Desalination	5-9	Demand

3.2.2 Offshore wind and green hydrogen

Offshore wind power can be used to produce green hydrogen. The idea of using the excess offshore wind energy to make hydrogen has sparked great interest in governments to move towards greener energy systems over the next 30 years under the terms of the Paris Climate Agreement [55]. However, offshore wind farms could also be thought to have some or all dedicated capacity to produce green hydrogen; in this case, not only would excess wind energy satisfy the demand for green hydrogen production.

Hydrogen can be produced using a wide range of electrolysis systems, such as alkaline water electrolysis, proton exchange membrane electrolysis, and solid oxide electrolysis of water. There are others under development that may become important in the future. The process of offshore wind power hydrogen production involves combining offshore wind power and purified water from the ocean to generate hydrogen and oxygen continually. According to the International Energy Agency (IEA), total offshore wind capacity is forecasted to triple by 2026, reaching close to 120 GW [56]. With such an ambitious target, a new era of offshore hydrogen production of industrial volumes is beginning [57].

Offshore hydrogen production is currently being developed in various concepts to bring far offshore or floating wind to shore [58]. The state-of-the-art technology is putting hands on practice dealing with commercial technological offshore wind turbines available in the market, a floating platform and an electrolyser unit. The floating platform is anchored to the seabed and sustains the offshore wind turbine and the electrolyser unit (Figure 3.2). The wind turbine will power the desalination equipment to remove salt from seawater, and the electrolyser to split the resulting freshwater into oxygen and the sought-after hydrogen, which is sent ashore via pipes.



(a) (b)

Figure 3.2: (a) State-of-the-art concept to produce hydrogen via offshore wind. Source ERM Dolphyn Project [2], (b) State-of-the-art concept (Donghae 1) for an offshore wind park plant to produce hydrogen in Korea [3].

It is expected that large-scale hydrogen electrolysers will become more available while the costs of installing wind turbines drop [59]. In terms of energy storage, some companies have already started to design compact systems to store hydrogen and fit them into a single wind turbine, such as the Oyster consortium [4] that hope to have a shown-off demonstrator system (Figure 3.3) by the end of 2024. Other companies have created other business concepts, such as the one conceived by SwitcH2 (`https://switch2offshore.com/`), which is based on off-grid FPSOs (Floating production storage and offloading) vessels that can go anywhere offshore and connect to wind farms to get the electricity needed for green hydrogen production and its transformation into ammonia. The ammonia would be, in this business model, the commodity to trade.

Offshore hydrogen production is still in its early stages of development and there are some challenges that need to be addressed. One of the main challenges is the cost of producing hydrogen offshore, which is higher than onshore because of the additional costs associated with transporting equipment and personnel to offshore locations. Another challenge is the harsh environment that offshore wind turbines are exposed to, which can cause corrosion and other damage to the equipment.

Figure 3.3: ITM Power Energy storage via hydrogen pumped by offshore wind. Source Oyster Project [4].

3.2.3 Network forming converters

Increasing penetration of renewable power sources into existing power grid networks

In recent years the generating power systems have quickly changed from the traditional spinning electromechanical generation power stations, generally driven by fossil fuels or water from water dams. These traditional power-generating systems were generally the dominant power sources in the existing power grids, with passive customer loads. These generators were mainly synchronous rotating machines with large inertia, providing stable and fully controllable operations to the existing energy distribution grids [12, 60–66].

With the emergence of other renewable sources of energy that integrate into the existing grids, namely those based on intermittent sources, like wind or solar, the characteristics of these power generators changed, and those sources are now non-synchronous. As such, there is always the necessity to interface renewable power sources to the grid network using some kind of electronic devices that convert and control the characteristics of the delivered power waveform to the AC waveform specifications of that power distribution grid network.

A power electronic inverter/converter device converts power from an energy power resource to AC power for use in an AC grid power system. These power electronic devices include a set of switching semiconductor devices and a grid-side passive filter that prevents switching harmonics from propagating into the grid. The input side of these devices connects either directly with an energy source or might be connected to additional power electronic devices, as DC-to-DC converter(s). The power inverter/converter device requires a closed-loop control to accomplish the grid network's functional specifications and stability requirements to which it will connect. Nowadays, in modern converters, these closed-loop controllers are in the form of a fully programmable digital controller. These digital controllers are based on controlling software algorithms that can be modified according to the power source and grid network characteristics [62, 66–68].

This transition to a grid network with more of these power converters or inverter-based resources (IBRs) introduces major challenges because the operation of these network power grids must combine the physical properties and control responses of traditional, large synchronous generators as well as the distinct characteristics of numerous and diverse inverter-based resources, distributed and active in the network [62].

Nowadays, power grids integrate increasing amounts of IBRs, mainly based on wind, solar and battery storage sources, and some regions will surpass penetration levels of 50 to 60 % of system demand. By 2025, various European countries, are projected to experience periods in which these IBRs-based power sources will serve 100 percent of the load [60, 62, 63, 69, 70]. As a result, as traditional power plants are taken offline, the grid's strength will decline in some of those regions. Consequently, in regions experiencing high instantaneous levels of renewables and other IBRs devices or generators, the power grid may not always possess the system strength required by the different national grid codes. As the penetration of intermittent power inverter-connected generation increases, resultant power stability and quality issues arise (e.g. harmonics, flicker, and voltage unbalance, frequency stabilisation), requiring new robust methodologies and mitigation strategies for implementing and controlling these new grid structures [60, 67, 69, 71].

More advanced technology is needed, and the so-called Network Forming converters or Grid-Forming inverters/converters, as in the technical literature, will certainly play an important role [60, 61, 69, 70].

Grid network forming technologies

There are two main types of devices to interface power sources to the AC grid networks: the grid following and grid forming inverters or converters.

Conventional power plants that run on natural gas, coal, nuclear fuel, or hydropower, produce electricity with synchronous generators—large rotating machines that produce AC electricity at a specified frequency and voltage. These generators have a natural tendency to synchronise with each other, which helps to make it possible to restart a grid that is completely blacked out. A generator has a large rotor rotating mass that, when spinning, cannot stop quickly, as it can weigh well over 100 tons. This gives rise to system inertia, which arises naturally from those large generators running synchronously with each other. Over many years, this was used to determine how fast a power grid will change its frequency when a failure occurs, and mitigation procedures could be developed based on that information. Modern electricity power grids are designed so that even if the network loses its largest generator, running at full output, the other generators can pick up the additional load, so that the output AC waveform frequency never falls below a specific threshold. As long as the frequency remains within the grid specifications, local blackouts are unlikely to occur [61, 63, 69–71].

As traditional power plants become fewer in number due to the increasing penetration of inverter-based power sources, the grid system's inertia lowers, meaning that system frequency may fall faster after disturbances within the grid due to some device failures or instability. This could cause some grid-following inverters to lose their synchronisation or stability with the grid system and disconnect.

A grid-following inverter/converter controller contains two main subsystems: a Phased-Locked-Loop (PLL) that estimates the instantaneous angular difference between the grid measured and the converter terminal AC voltage and a current-control loop that regulates the AC current injected into the grid. This is generally mentioned as a current control strategy because the current is the physical quantity that is regulated.

The traditional grid-following electronic inverters are dependent on other existing stable grid power sources to synchronise to, and that is the reason for the term grid-following inverters or converters. These inverters cannot directly adjust the voltage or frequency of the grid: if a grid-following inverter loses the voltage/frequency source, it must be turned off, and it cannot start up itself. Today, almost all inverter/converter controllers connected to the grid networks are grid-following. As a result, the grid's stability may be endangered, if production based on synchronous power generators is not available or does not guarantee the system's inertia to other sources instability and, in case of excess renewable energy source penetration, some curtailment must be made, to avoid cutoff the traditional synchronous power sources from the grid [12, 64, 65, 70, 72].

As so, in regions with high instantaneous levels of renewable energy sources based on IBRs, the grid strength, stability and reliability may suffer, beyond the grid's code requirements, and more advanced inverter devices are required to control all those power sources within the power grid. Operation and control strategies to ensure that intermittent sources inverter-connected generators contribute in a reliable way to grid network stability and reliability require new control methods and strategies and the more recent grid-forming inverters can be the key.

The main idea for these recent Grid-Forming inverters was proposed for the first time in 1993. The goal was to supply the load through the parallel connection of these inverters, without the need to interface control signals between them. In other words, each inverter device was able to control its own outputs locally. In 1998, this control idea was extended to converters interfacing with renewable energy generators and energy storage systems within microgrids. These inverters/converter devices are called Grid-Forming, and act as a voltage source within a specific range in the grid. By actively controlling the frequency provided by these new source devices, it is possible to reduce the dependency of the grid's frequency dynamics on mechanical inertia and provide better control of frequency fluctuations in a complex grid system [62, 63, 69–71].

The main difference between grid-following and grid-forming converter devices is the ability to control the main output parameters differently. A grid-following converter can inject a constant power independent of the connected grid's power source state and rely on their existence to maintain its output AC voltage and frequency characteristics. On the other hand, a grid-forming has complete control over its output voltage and frequency, when acting as a voltage source.

A key aspect differencing the grid-forming inverters/converters and the more traditional grid-following counterparts is the embedded control software. Grid-forming devices are controlled by software embedded code designed to maintain a stable output voltage waveform, while allowing the magnitude and phase of that waveform to change over time, always keeping the possibility of that waveform's magnitude and frequency to synchronize with other grid nearby power generators [12].

Grid-forming devices can be designed with a tighter tolerance for voltage and frequency deviations and respond to these conditions in ways that benefit the overall grid network system. For instance, grid-forming devices can be designed to provide system restoration services after a blackout, including energy storage units, which grid-following devices cannot [12, 72, 73].

Even though there are no significant cost differences in the electronic hardware of these devices, the costs for developing and manufacturing grid-forming converters are still higher than for today's converters, due to the need for some oversized components and new software control strategies. Also, some new required functionalities and the expected better performance of grid-forming devices are not uniform across the several national grid power networks, and this can also drive up the development cost of these systems.

Common requirements for the national and regional grid-codes are needed to guide manufacturers in developing and supporting new grid-forming products and devices, reducing the complexity and costs. This also requires that equipment manufacturers work closely with grid operators and developers to better define which are the best solutions and device capabilities in different situations, whether through simulation or operational practice. Such collaboration is important for optimizing the additional technical capabilities required and, consequently, for lowering the cost of grid-forming technology deployment [12, 65, 70, 74].

Table 3.2: Comparison of grid-forming and grid-following interfacing technologies (adapted from [12]).

Grid-following	**Grid-forming**
Similar to a constant current source	Similar to a constant voltage source
Inability to directly control the frequency or voltage of the grid	Can adjust output frequency and voltage dynamically
Intensification of instability of frequency and/or voltage in case of increased penetration	Improved system frequency response in case of increased penetration
Black start capability is not possible, and the power source must be shut down if voltage/frequency is lost	Provide system's black start capability, after a blackout
Inability to work with 100% penetration of inverter-based power sources	Ability to work with 100% penetration of inverter-based power sources, at least in theory
PLL type of control feedback required	Does not use PLL based control feedback
Currently the largest share of technology in inverter-based power sources	Currently a small share of technology in inverter-based power sources

Some progress in standardisation is already undergoing in several regions of the world. In the United States, for example, the North American Electric Reliability Corporation (NERC) recently published a recommendation that all future large-scale battery-storage systems have grid-forming capability [75]. Also in the United States, the Universal Interoperability for Grid-Forming Inverters (UNIFI) Consortium, led by the National Renewable Energy Laboratory (NREL), the University of Texas at Austin, and the Electric Power Research Institute (EPRI), aims to address the fundamental challenges in integrating very high levels of inverter-based resources with synchronous generators in power grids. The consortium now has over 30 members from industry, academia, and research laboratories [62, 74–77].

Standards for grid-forming converters performance and validation are also starting to emerge in some countries, including Australia, Finland, and Great Britain. The European Network of Transmission System Operators for Electricity (ENTSO-E) has also some work done in unifying grid-codes at the European level to include these new requirements for grid-forming converters in the various power grid networks [62, 78, 79].

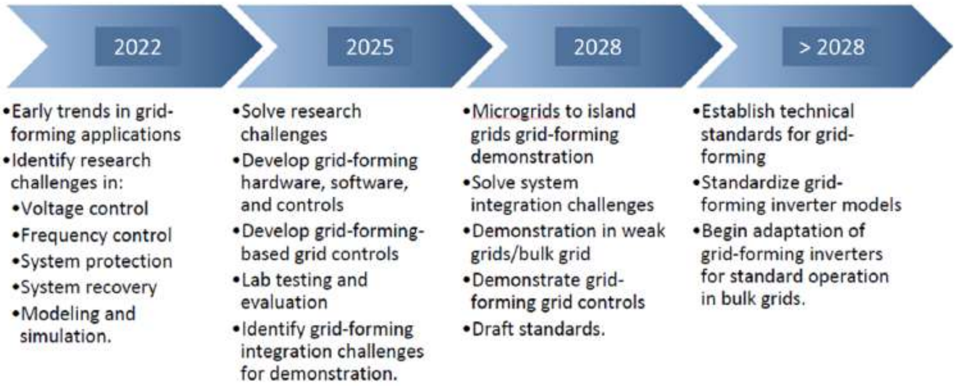
Grid-forming converters are already available from several leading manufacturers [62]:

- Grid-forming inverters for utility-scale batteries are available today from Tesla, GPTech, SMA, GE Vernova, EPC Power, Dynapower, Hitachi, Enphase, CE+T, and others.
- Grid-forming converters for High Voltage Direct Current links (HVDC), which convert high voltage DC to AC waveforms and vice versa, are also commercially available, from companies including Hitachi, Siemens, and GE Vernova.
- For photovoltaics and wind, grid-forming inverters are not yet commercially available at the size and scale needed for large grids, but GE Vernova, Enphase, and Solectria are now

developing them.

Power system stability and protection are foundational technical issues for any power grid network structure, and the development of grid-forming converters is still in the groundwork stage. Future road mapping will need to address various topics that still require further research, development, and testing, for power grid networks with almost 100% penetration of grid-forming converter-based power sources [80–83]:

- Distribution system engineering and operations for grid-forming converter controls, a grid of microgrids and effective dynamic islanding topology solutions, unintentional islanding on distribution grids;
- Evolution of sensing and communications systems;
- Various power quality issues (e.g., harmonics), hybrid AC-to-DC systems, system costs analysis, considering the growth of power electronics-based loads and their control;
- Economic dispatch, system adequacy, and reserves assessments for power electronics dominated grids;
- Traditional security evaluation (i.e., contingency analysis, black-start);
- Market design, economic regulation, and cybersecurity.


2022

- Early trends in grid-forming applications
- Identify research challenges in:
  - Voltage control
  - Frequency control
  - System protection
  - System recovery
  - Modeling and simulation.

2025

- Solve research challenges
- Develop grid-forming hardware, software, and controls
- Develop grid-forming-based grid controls
- Lab testing and evaluation
- Identify grid-forming integration challenges for demonstration.

2028

- Microgrids to island grids grid-forming demonstration
- Solve system integration challenges
- Demonstration in weak grids/bulk grid
- Demonstrate grid-forming grid controls
- Draft standards.

> 2028

- Establish technical standards for grid-forming
- Standardize grid-forming inverter models
- Begin adaptation of grid-forming inverters for standard operation in bulk grids.

Figure 3.4: Grid-forming converters research and development roadmap (reproduced from [5]).

Presently, some small island power grid networks are already operating at or near 100% wind and solar, which include basic grid-forming controls supported by energy storage. The Maui, Hawaii, (USA) is one such example [62].

Scaling from smaller systems to more complex grids will require a maturing of grid-forming inverter controls for new grid power system stability design. Replacing totally synchronous machines with grid-forming converters will have a relatively long timeline (~10–30 years) and will be achieved only when solid research base results for protection, controls, and interoperability have been established and a robust environment of standards for grid codes exist, defining the required functionality of grid-forming converters on the different kinds of power grid network [80, 83].

3.2.4 Offshore wind power plant power transmission

The deployment of offshore wind farms or power plants (OWPPs) and the increased penetration of such large-scale OWPP in grid power networks results in increased power quality and grid system stability issues, due to the operational modes (standalone or grid-connected) and structural and performance constraints posed by these OWPP.

The intermittent nature of wind power poses various challenges related to the transmission of energy and integration in grid network systems of OWPP turbines. Several stability aspects of the OWPP connected to the grid networks have been reported in recent technical studies, including steady-state frequency control, damping control, voltage control, and transient stability control.

Wind Turbine Generator (WTG) manufacturers and offshore wind power plant (OWPP) developers are competing for the larger wind turbine and wind power plant capacity, leading to grid connections being considered a critical topic. The increased capacity and the location of OWPPs, farther from shore, bring also new challenges in terms of power transmission over longer distances. In addition, grid network operators require OWPPs to not only fulfil grid codes but also contribute to improving grid resilience and providing ancillary services [66–68].

Traditional High Voltage Alternating Current (HVAC) transmission is being used extensively in offshore-based farms due to its simple design and mature technology. From the design perspective, HVAC has the advantage of cost (cheaper, due to the lack of converter stations) compared with HVDC for distances to shore between 80–100 km. However, HVAC technology is more dependent on the resilience of the power grid network. It requires a system integration approach and integrated system design studies for reactive power compensation, steady-state harmonics, and voltage and frequency stability [67, 84].

More recently, OWPP with HVDC power transmission has risen as the most viable technology to transfer power from large OWPPs to onshore grids over distances of more than 80-100 km, mainly due to the significantly lower transmission losses. HVDC solutions are typically voltage source point-to-point approaches, with significant research and development being carried out to explore other possible design options [67, 68, 84].

3.2.5 Offshore wind power plants grid network interconnection

In the past few years, various schemes for OWPP to grid interconnection have experienced significant progress. Regulatory grid codes outline these technical requirements and responsibilities for modern OWPP grid network interconnections. In Europe, the European Network of Transmission System Operators for Electricity (ENTSO-E), which comprises about 39 transmission system operators, has progressed towards harmonizing the grid network codes across five regions within Europe (the ENTSO-E Requirements for Generators (ENTSO-E RfG)) [78, 79, 85]. However, there is still a need for further harmonising the existing grid codes to other regions to reduce the extra excessive WTG parameterisation of devices and minimise the need for different types of OWPP using standard interface controllers to interconnect to network grids with different types of regulatory requirements.

The frequency and voltage operating ranges are the most basic requirements for OWPPs to remain connected to the grid. Both active power and frequency control contribute to the frequency stability of wind power plants [67].

The OWPP grid integration control can be generally classified into two strategies: the wind turbine generator level and the global wind power plant level. The WTG control includes the most fundamental control strategies that determine whether the OWPP fulfils the key requirements of grid codes and the stability of the OWPP. However, the power plant-level controller is preferred in a modern OWPP to achieve an accurate closed-loop regulation to comply with regulatory grid codes [66–68].

As referred before, as the deployment of renewable generation is rapidly increasing in power systems across the globe, grid-forming control has been given special attention, and it is expected to stabilise the grid networks in the absence or low level of synchronous generators. Similar to other IBRs connected to a power system, wind turbines can be controlled as either grid-following or grid-forming sources if they are equipped with power electronics converters to control the power flow. The control type conversion generally requires minimum hardware modification because the inverter control behaviour can be mostly determined by the control software. It indicates that converters can have a mode transition during operation, e.g., between island and grid-connected modes, which is useful for flexible operation and resilience[4].

The grid-forming type of control for OWPPs is currently under active research and demonstration. It is motivated by the unique aspects of offshore wind, such as the long distances from the onshore grid causing a weak grid condition that makes it prone to oscillation and instability. By using grid-forming control, it is expected that OWPPs can stabilise when integrating weaker grid networks by forming reliable voltage profiles and mitigating oscillations. The active exploration of using grid-forming controllers for offshore wind is also revealing their potential to provide grid services to enhance OWPP's added value, such as bottom-up black start to recover a local grid for resilience and support for bulk power system restoration [66–68, 86].

This type of control for offshore wind power plants would be beneficial for grid stabilisation and grid resilience enhancement by allowing the wind power plants to have more active and dynamic roles in power system operations. The technical merits of and trade-offs between GFL and GFM inverters, however, should be clearly understood and thoroughly evaluated through research, development, and field demonstrations.

The inclusion of energy storage systems will also play a significant role in the power quality improvement of the OWPP-generated power, by helping to regulate its output voltage. These storage systems generally may include batteries, supercapacitors, pump hydro and hydrogen production [65, 87, 88]. They can provide smooth output and system flexibility from wind generation for a specific time duration in case of any fault, providing also the capability of "black-start" of these systems in case of a system fault or blackout. The integration of Power-to-X technology devices, including using hydrogen as an energy storage buffer—is appealing, but still requires deeper research in the near future [66, 67].

3.3 Water desalination

3.3.1 Water for hydrogen production

Water electrolysis uses electricity to split water into hydrogen and oxygen. Water demand for hydrogen production via electrolysis is about 9 kg of water per kg of hydrogen. This value is usually increased due to losses or inefficiencies in the system, reaching values of about 12 kg of water per kg of hydrogen.

In regions prone to water supply stress, seawater desalination is required. It has been reported that the use of desalination systems for Power-to-X systems requires about 0.15% of electricity for the desalination process [89]. A sustainable management process of the Power-to-X system shall consider other aspects, such as the treatment or sustainable disposal of the brine effluent (a concentrated salt solution that must be properly disposed of to avoid adverse impacts on the coastal environment).

When seawater is used directly in electrolysis the same electrical jolt that generates O_2 at the anode also converts the chloride ions in saltwater into highly corrosive chlorine gas, which eats away at the electrodes and catalysts. This typically causes electrolysers to fail in just hours when they can normally operate for years. Recently, some groups have reported efforts to halt this corrosion [90, 91]. Despite the resources and efforts that have gone into developing this technology, direct seawater splitting remains in its infancy and distant from commercialisation [92].

3.3.2 Desalination

Desalination is the process of removing salt from the sea (or brackish water) to make it usable for a range of ’fit for use’ purposes, including drinking purposes and water electrolysis. This summary only refers to the use of ocean water to produce green hydrogen. In the next subsection, desalination technologies are described.

Desalination technologies

Desalination technologies consist of thermal and membrane separation processes. Thermal desalination technologies are multi-effect distillation (MED), multistage flash distillation (MSF), and vapour compression (VC), which can be either mechanical (MVC) or thermal (TVC) [93, 94]. The most common membrane-based desalination processes are reverse osmosis (RO) and electrodialysis (ED). Other membrane processes like forward osmosis (FO) and membrane distillation (MD) are still emerging and have not yet passed the pilot plant stage, as others, like capacitive deionisation (CDI), pressure retarded osmosis (PRO) and adsorption desalination (AD). Hybridisation of different desalination technologies can be an effective approach to minimise energy requirements and overcome the operational limitations of conventional treatment methods [13].

Membrane distillation (MD) has attracted much attention due to its potential for increased sustainable water production. MD is a membrane-based thermal desalination process, which uses a hydrophobic membrane to separate hot and cold streams of water. Instead of a pressure or concentration difference, the driving force for the MD processes is the vapour pressure difference across the membrane. The saline feed side is heated prior to contact with the cooled permeate side, after which the water evaporates at the membrane-solution interface. This results in a distillate which is of very high quality.

All thermal desalination processes, except MVC, require two forms of energy: low-temperature heat to raise the temperature of the saline feed and electricity, which is used to drive the pumps. Membrane-based processes, reverse osmosis (RO) and electrodialysis (ED), only use electrical energy: in RO, electricity is used for pumping, while in ED, it is used to supply a direct current between electrodes to achieve separation of ions by ionic membranes.

In reverse osmosis (RO), membrane fouling causes a decline in membrane permeability with time. To operate at the same set flux, the applied pressure should be increased. This means that during RO operation, pressure requirements are variable. Over the past decade, advancement in RO membranes has contributed significantly to the decrease in SEC of SW desalination [13].

Thermal desalination technologies have been replaced with membrane-based processes in many parts of the world, but in some parts of the world such as the Gulf are still prominent, with the plentiful supply of oil for energy, frequent occurrences of algae bloom, and the operational limitations of RO for the treatment of high SW feed salinities and turbidity [13].

The amount of energy consumed in multi-stage flash (MSF) depends on many factors: the temperature difference between the heat source and heat sink, the salinity of feed water in the flashing stages, process configuration, construction material, number of stages, and type of heat-exchanger devices. Another significant factor which affects energy consumption in MSF is scaling or fouling. At high temperatures, different types of salts, like magnesium hydroxide, calcium carbonate, and non-alkaline scales, form deposits. These deposits plug the heat exchanges leading to reduced heat transfer rate and lower heat transfer efficiency. Besides that, scaling can increase SEC and operating costs [13].

Multi-effect distillation (MED) is one of the oldest desalination technologies. In its early stages of development, MED suffered from significant scaling problems. In the 1960s, MSF was introduced and replaced MED because the former had less severe scaling issues. However, the thermal energy requirements in MED are lower than MSF. This is because MSF requires large amounts of high-temperature steam to boil water at top brine temperature (TBT) close to 100 °C, whereas in MED water is boiled at a lower temperature (70–90°C) as the pressure is lower than the atmospheric pressure [13]. MED consists mainly of a condenser and multiple effects. Initially, saline feed water enters the condenser tubes where it gets preheated. Then, usually, heated feed water is fed to the multiple effects in equal proportions. In each effect, saline feed water is sprayed on the outer surface of evaporator tubes. In the first effect, water sprayed on the evaporator tubes vaporises as it absorbs heat from low-pressure steam inside the tubes. Steam condenses as it loses its energy to the saline water. Vapour formed from the evaporation of feed water is used as an energy source in the successive effects. Vapours from the last effect are used to preheat saline feed water in the condenser. As a result, these vapours condense to yield fresh water.

Seawater desalination costs

The amount of energy required for a desalination process is dependent on the quality of feed water, level of water treatment, treatment technology used by the facility, and plant capacity and is shown in Table 3.3. Desalination operating expenditure (adapted from [13]). For thermal desalination processes, which consume a large chunk of energy for heating, renewable energy sources can be a viable option for bringing down the energy requirements.

The total water production costs vary with the feed water type, the energy type, and the capacity of the plant. Table 3.4 presents the unit cost in Euros per cubic meter of seawater desalinised.

Figures for seawater desalination:

- A minimum energy of 1.06 kWh/m^3 is required to desalt 35 ppm salt water, with a typical recovery of 50%.
- Most SWRO plants operate in the recovery range from 45 to 55%.

Table 3.3: Desalination operating expenditure (adapted from [13]).

Type	**Desalination – Operating expenditure by service**	
Chemicals	16,8%	
Labour	24,4%	
Replacements	12,2%	Membranes 48,2% Parts 51,8%
Energy	46,6%	Surface water (lake or river) 0,37kWh/m^3 Groundwater 0,48 kWh/m^3 Wastewater treatment 0,62-0,87 kWh/m^3 Wastewater reuse 1-2,5 kWh/m^3 Seawater 2,58 – 8,5 kWh/m^3

Table 3.4: Capacity of desalination unit and cost of water produced from seawater (adapted from [13–15]).

Capacity of the plant (m^3/d)	**Cost (€/m^3)**
<1 000	1.78 – 9.00
1 000-5 000	0.56 – 3.15
12 000-60 000	0.35 – 1.30
>60 000	0.40 – 0.80

- High-pressure pumps (HPP) are the major energy consumers in RO plants, and at most times, selection amongst the best available pump is the only choice which can be made for an optimum working point. Energies from these contribute to almost 75% of the total specific energy, while the remaining comes from the membrane.

- Desalination technologies present differences in terms of energy efficiency, level of pretreatment required, fouling and selectivity. Table 3.5 summarises their characteristics, where one star refers to poor and three stars refer to excellent performance.

Table 3.5: Qualitative comparison of desalination technologies (adapted from [13]).

Metric	**MD**	**RO**	**MED**	**MSF**
Energy efficiency	★☆☆	★★★	★★☆	★☆☆
High-salinity feedwaters	★★★	★☆☆	★★☆	★★★
Small-scale operation	★★★	★★★	★☆☆	★☆☆
Utilizing low-grade energy	★★★	★☆☆	★★☆	★☆☆
Fouling resistance	★★☆	★☆☆	★★☆	★★★
Low pretreatment	★★☆	★☆☆	★★★	★★★
Low lifetime costs	★☆☆	★★★	★★☆	★★☆

There is a wide range of lower TRL desalination technologies in addition to more mature technologies, most of them related to hybridisation. Figure 3.5 illustrates the cost, capacity and the development stages of various RE powered desalination technologies.

3.3.3 Brine disposal

Brine, also known as concentrate, the concentrated salt solution generated from desalination, has received a lot of attention around the world due to its adverse impact on the environment, due to its toxicity and even the corrosion of infrastructure, making brine management systems needed to reduce environmental disturbances.

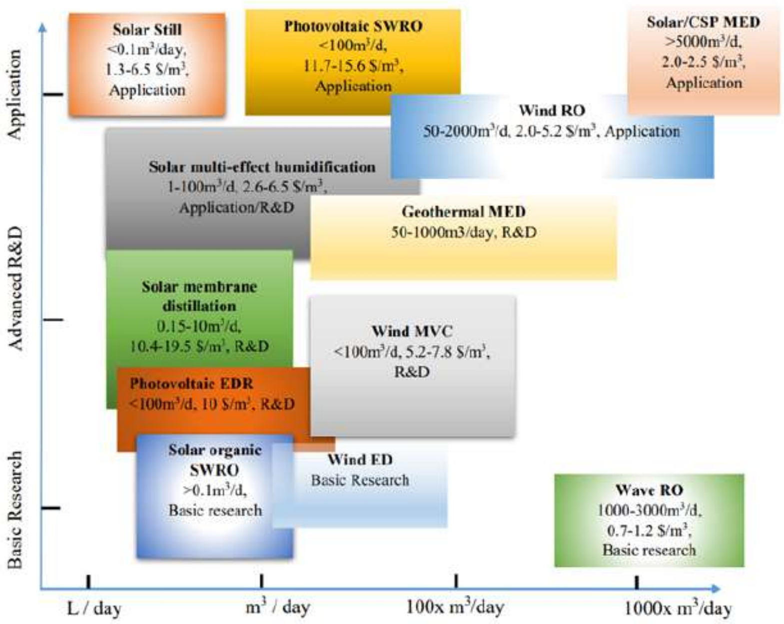


Figure 3.5: Renewable energy operated desalination technologies status: Capacity, production cost & technology trend (reproduced from [6]).

Various disposal methods have been practised, such as surface water discharge, sewer discharge, deep-well injection, evaporation ponds and land application. However, these brine disposal methods are unsustainable and restricted by high capital costs and non-universal application and do not integrate minimisation of waste volume and production of freshwater with material recovery [95]. To tackle this problem, brine treatment and valorisation is considered a promising strategy to eliminate brine discharge and recover valuable resources such as water, minerals, salts, metals, and energy [96].

Brine has a high salinity and may contain dangerous pretreatment chemicals (e.g., residual amounts of antiscalants, coagulants and flocculants), organics and heavy metals. Potential environmental damage includes eutrophication, pH fluctuations, an increase of heavy metals in marine environments, etc. [95].

The main environmental concerns associated with brine disposal are: increased salinity of receiving water bodies and soil, regional impacts of high-TDS brine on marine benthic communities near the discharge point, esthetic problems, disposal of pretreatment and membrane cleaning chemicals, disposal of corrosion metals such as copper (Cu), ferrous (Fe), nickel (Ni), molybdenum (Mo) and chromium (Cr) [95].

Several studies have shown that even a slight increase in salinity can be harmful to marine life as it disrupts the osmotic balance of marine species with their environment. This disruption leads to cell dehydration and a decrease in turgor pressure and may lead to the extinction of species in the long term. However, some examples of ocean outfalls have been used in areas with abundant currents, and thus no negligible impacts have been observed on the marine flora and fauna. Recent studies have suggested that the long-term impact of brine disposal in outfall areas could be mitigated by using multiport diffusers [95].

3.3.4 Brine valorisation

Nowadays, the management and valorisation of waste brines, also aiming at the recovery of raw materials, are gaining more importance. Circular strategies should be implemented to purify the effluents and recover raw materials to reduce the environmental impact of the industrial sectors.

The minerals/salts composed of major ions (i.e., Na+, Cl-, Mg2+, Ca2+) can be useful in various sectors, and their sale prices are reasonable. On the other hand, the extraction of scarce metals such as lithium, rubidium, and cesium can be extremely profitable as their sale prices are extremely higher compared to the sale prices of common salts [96].

For instance, Magnesium has been listed as a Critical Raw Material by the EU, prompting researchers to investigate novel routes for its recovery. Within this framework, a novel Crystalliser with Ion Exchange Membrane (CrIEM) is proposed as an innovative way to recover magnesium from industrial waste brines, exploiting low-cost alkaline reactants [95].

Lithium's scarcity has raised concerns about battery and can justify its recuperation from brine from Seawater. The world's oceans contain an estimated amount of 180 billion tons of lithium. But it is diluted, present at roughly 0.2 parts per million. To date, such efforts have not proved economical [97]. Nonetheless, the extraction of such precious metals is currently restricted to a laboratory scale.

Besides water, minerals, salts, metals, and energy can be harvested from brine. In particular, salinity gradient power can be generated. Salinity gradient power technologies have shown great potential in several bench-scale and pilot-scale implementations. Nonetheless, several improvements are required to promote their large-scale feasibility and viability [96].

3.4 Electrolysis for hydrogen production

Water electrolysis is a process that uses electricity to split water into hydrogen and oxygen. It is considered a central component of Power-to-X solutions. The three main water electrolysis technologies currently available are alkaline electrolysis, proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis. The first two technologies operate at low temperatures (70-90°C for alkaline and 50-80°C for PEM), whereas solid oxide electrolysis operates at high temperatures (700-850°C) [98]. Although solid oxide electrolysis has high potential, it is still in the development stage, and only a few companies are working on its commercialisation. This study focusses on the most mature water electrolysis technologies, namely alkaline and PEM electrolysis. Table 3.6 lists the selected key performance indicators for both technologies.

Alkaline electrolysis has been used industrially for more than a century, leading to well-optimised designs and mature supply chains. It uses a basic liquid electrolyte (usually an aqueous solution of potassium hydroxide at a concentration of 5-7 mol/L) and a porous inorganic diaphragm to separate the gases produced [98]. The main advantage of alkaline electrolysis is its use of earth-abundant and inexpensive materials. This, along with its commercial maturity and relatively low degradation rate, makes it the most cost-effective electrolysis technology on the market. However, its disadvantages include a lower nominal current density, which negatively impacts land footprint and hydrogen production costs, and a slower dynamic response, making it less ideal for coupling with variable renewable electricity supply.

PEM electrolysis is a less mature technology but is already available at a multi-megawatt scale. It uses an acidic polymer membrane sheet as both a solid electrolyte and gas separator. This technology is characterised by a faster response time, making it the most suitable for connection to variable renewable electricity. Other characteristics include its ability to operate at higher current densities, thereby reducing land footprint and hydrogen production costs. However, certain raw materials used in the stack manufacturing process, such as electrocatalysts and membranes, can be problematic because of cost, availability, and lower durability.

Table 3.6: Key performance indicators for alkaline and PEM technologies.

Parameter	**Alkaline**		**PEM**		**Unit**
	2020	**2030**	**2020**	**2030**	
Electricity consumption	50	48	55	48	kWh/kg
Hot idle ramp time	60	10	2	1	s
Cold start ramp time	3600	300	30	10	s
Degradation	0.12	0.1	0.19	0.12	%/1000 h
Current density	0.6	1	2.2	3	A/cm^2
CRM catalyst usage	0.6	0	2.5	0.25	mg/W

3.5 Sustainable fuels: Synfuels

Synthetic biofuels are considered a crucial component of circular economy strategies as they contribute to the efficient use of resources and waste. The main advantages of the synthetic fuels are:

- **Efficiency**: Their physicochemical properties are similar to regular fuels, making them compatible with current vehicles and allowing for existing infrastructure to be used.
- **Sustainability**: Alternative and renewable raw materials can be used in their production.
- **Strategy**: Contribution to the progressive decarbonisation of heavy transports and aviation.
- **Innovation**: The development of technologies for synthetic fuel production based on renewable sources will contribute to low emissions and enhance technologies for producing renewable hydrogen.

3.5.1 Power-to-HVO

The most developed synthetic fuels using hydrogen are the hydrotreated vegetable oil (HVO), which can be produced from various vegetable oils and fats. It contains triglycerides and fatty acids. HVO is also called Hydro-processed Esters and Fatty Acids (HEFA). HVO is produced by hydrogenation and hydrocracking of different feedstocks such as tall oil, rapeseed oil, waste cooking oil, and animal fats, using hydrogen and a specific catalyst at high temperatures (300 – 390°C) and pressures.

In this process, oxygen is removed from the feedstocks, producing mainly straight-chained hydrocarbons (paraffins). The conversion usually occurs in two stages. The first one is the hydrotreatment process and the deoxygenation of fatty acids, during which straight-chain alkanes form through the saturation of double bonds. In the second stage, the cleavage of long-chain alkanes to shorter ones takes place, as well as the isomerisation process. HVO does not contain sulphur, oxygen and aromatic hydrocarbons, and has a high cetane number. Overall, it has a similar chemical composition and properties as fossil diesel, so it can be used as a renewable fuel in existing diesel engine vehicles (pure or blended). The main differences are its lower density and energy content. However, its properties and molecular size range depend on the feedstock characteristics and process conditions. HVO has also been approved to be used as an aviation (bio jet) fuel, being allowed to incorporate up to 50% biobased components (HVO) into conventional jet fuel. Therefore, it is considered an important alternative in the implementation of renewable aviation fuels. Furthermore, it is already ASTM-certified and has demonstrated high technological maturity.

In co-processing, the biobased components are fractionated in different refinery lines, originating multiple products, one of them is kerosene, used, for example, for jet fuel applications. To achieve a final product of jet A-1 grade, the biobased components undergo a process of refining different fractions, called distillates, which are obtained. Another possible refining process is cracking carbon chains to achieve the desired carbon length. The final products are jet fuel and a range of other hydrocarbon fuels and byproducts. HVO is refined to SAF through a process that uses hydrogen (hydrogenation). In the first step of the HVO process, oxygen is removed by hydrodeoxygenation. Next, the straight paraffinic molecules produced go through a cracking and isomerisation process to adjust the hydrocarbons' chain length to jet fuel. The process is similar to that used for hydrotreated renewable diesel production, but with more severe cracking of the longer chain carbon molecules [99]. So, on the conversion step of hydroprocessing, a higher oxygen to carbon and hydrogen content of the feedstock will increase the amount of hydrogen required. To be considered green, the hydrogen used must come from renewable sources. The hydrogen produced by water electrolysis powered by renewable energy, like solar or wind, can be easily used in the process.

3.5.2 Power-to-Methanol

Methanol, also known as methyl alcohol, has attracted great interest due to its potential fuel and chemical uses. It can be used directly or blended with other petroleum products as a clean-burning transportation fuel and is also an important chemical intermediate used to produce several chemicals.

Methanol synthesis is still attracting interest even though the current technology process was developed long ago. However, the main interest now is in green methanol. Its use instead of fossil fuels can reduce greenhouse gas (GHG) emissions and, in some cases, can also reduce other emissions such as sulphur oxides (SOx), nitrogen oxides (NOx), particulate matter (PM), etc. The growth of green methanol as an alternative fuel to fossil fuels is especially attractive to the maritime industry since, being liquid at room temperature, it is much less costly to store and transport than gaseous fuels and has the lowest carbon footprint of all liquid fuels. It can also be used in both internal propulsion engines and fuel cells, providing flexibility depending on the end use.

Renewable methanol can be produced from various sustainable feedstocks, such as biomass, waste, or CO_2 and hydrogen. There are two possible ways [100]:

- Biomethanol: produced from the gasification of sustainable biomass sources such as livestock, agricultural and forestry residues and municipal waste.

- E-methanol: formed from hydrogen produced from renewable electricity (called green hydrogen) and captured carbon dioxide.

Bio-methanol and e-methanol from renewable sources and processes are chemically identical to fossil fuel-based methanol but produce significantly lower GHG emissions during the entire life cycle. In this report, the focus is on the production of e-methanol using offshore wind.

Three main steps to be considered in the production of e-methanol are:

1. H_2 generation by water electrolysis,
2. CO_2 capture, and
3. Methanol synthesis.

These steps are described below.

1. **Step 1. H_2 generation by water electrolysis.** Hydrogen production by water electrolysis is a mature technology with actual efficiencies of about 75-85% for alkaline and PEM-based electrolysers. Solid oxide electrolysers are also being developed to offer higher efficiency by operating at much higher temperatures ($>$ 700°C). Any form of energy can generate the electricity needed for the process. However, to be sustainable, it needs to come from renewable sources or a low-carbon process. Wind and solar PV have the greatest potential for the large-scale deployment of sustainable electrolysis due to their increasing availability and decreasing costs. Some hydrogen storage capacity will also be needed to allow for the continuous operation of the methanol synthesis unit. On a large scale, the production cost of renewable H_2 is mainly dictated by the cost of electricity.
2. **Step 2. CO_2 capture.** The CO_2 feedstock for e-methanol production can be divided into two distinct categories depending on its origin:
   - Not renewable - come from emissions originated from electricity generation, cement and fermentation plants, industry, the transport sector, heating and cooling of buildings, and other activities. The CO_2 capture costs highly depend on its origin. Other CO_2 sources include fossil fuel power plants (coal, natural gas, oil), iron and steel plants and cement production. The technologies for large-scale carbon capture from fossil fuel power plants and industrial processes are relatively mature but need to be applied at the huge scale needed for the Power-to-X sector. It is worth noting that the current RED Directive will not allow the use of non-biogenic CO_2 for synthetic fuels after 2041.
   - Renewable – CO_2 can be obtained from the atmosphere directly by direct air capture or through biomass. In order to be renewable, sustainable, and CO_2 neutral, biogenic sources of CO_2 will have to be used, such as biogas, bioethanol, pulp, paper, and waste-to-energy. Biomass can provide part of the renewable CO_2 needed. However, the amount of CO_2 available from all the potential sources should allow the production of millions of tonnes of e-methanol per year. Nonetheless, CO_2 is also needed for other products such as e-kerosene and e-gasoline. So, given the amounts of CO_2 required in the long run, CO_2 capture from the atmosphere will also have to be implemented. CO_2

capture from air is performed at ambient temperature using several CO_2 sorbents. The captured CO_2 is then released by increasing the sorbent temperature and can then be used for methanol synthesis.

3. **Step 3. Methanol synthesis.** E-methanol is a liquid product obtained from CO_2 and hydrogen through a one-step catalytic process. Produced through a Power-to-X technology, e-methanol is considered is considered a renewable fuel of non-biological origin (RFNBO). The simplest and most mature method is to produce hydrogen through the electrolysis of water using renewable electricity, followed by a catalytic reaction with CO_2 to form e-methanol. In general, each molecule of CO_2 entering the process will exit as a methanol molecule. However, each CO_2 molecule requires three molecules of hydrogen and will produce one molecule of water for each molecule of methanol. The technology for the e-methanol synthesis step is very similar to that used to produce methanol from fossil fuel-based syngas; therefore, it is at TRL 8-9. The reaction occurs at temperatures between 200°C and 300°C and pressures of 50-100 bar. The $CuO/ZnO/Al_2O_3$ catalysts, normally used, are already available commercially and have only to be modified to tolerate the presence of larger amounts of water during e-methanol synthesis. The overall efficiency of e-methanol production is about 50-60%. A faster scale-up of the process can be achieved through the co-feeding of CO_2 and renewable H_2 into a traditional methanol fossil fuel-based plant. Another approach is the combination of bio- and e-methanol production in situ, which has the advantage of providing a source of CO_2 for e-methanol production and a hydrogen source for the complete conversion of the carbon contained in the biomass. During biomass gasification, a syngas mixture with a low H_2/CO ratio is generated, which needs to be adjusted to meet the optimal H_2/CO ratio for methanol synthesis, which is approximately 2. This is achieved with a WGS reaction creating excess CO_2. One of the possibilities to deal with this CO_2 and, simultaneously, increase the methanol conversion is to react it with green hydrogen, combining the bio-methanol and part of the e-methanol production processes [100].

3.5.3 Power-to-Ammonia

Ammonia has several advantages as synthetic fuel and energy storage. It contains no carbon, so its combustion does not produce CO_2. The manufacturing of ammonia is an established process, and therefore, the main challenge is to produce it carbon-free and, at the same time, cost-efficiently. Furthermore, large infrastructures for transporting and storing NH_3 have already been implemented. It can be easily stored as a liquid at atmospheric pressure by cooling to -33°C or pressurised at 9 bar at room temperature. The storage cost is low, and large amounts of energy can be stored without significant losses.

NH_3 is the second largest synthetic inorganic commodity produced worldwide, with 80% of the production used by the fertiliser industry. Presently, more than 90% of the world's ammonia production takes place through the catalytic process called the 'Haber–Bosch synthesis', which combines hydrogen (H_2) and nitrogen (N_2) [101].

The Haber–Bosch synthesis represents only the final stage in ammonia's production, and its responsible for a third of the energy consumed in the total process; the other two-thirds of the energy is spent on the generation of hydrogen and nitrogen. Before the NH_3 synthesis, both H_2 and N_2 need to be obtained, and their processes are very energy-intensive. Hydrogen production is often considered the first stage in the generation of ammonia and is currently mainly produced through steam reforming of natural gas. The use of the process for hydrogen generation is due to its high operational efficiency and low cost. Currently, steam reforming of natural gas is the least expensive method for hydrogen production. However, in this process, carbon dioxide emissions are unavoidable since they are a product of the chemical reaction. Thus, if the steps before ammonia synthesis are electrified, there will be a positive environmental impact and an efficiency improvement. The hydrogen production by electrolysis instead of steam reforming will increase the efficiency of the downstream processes. The high-purity hydrogen generated in electrolysis can help to prevent the inactivation of catalysts and avoid a more costly gas cleaning.

Another phase before the ammonia synthesis is the production of nitrogen. The advantage of nitrogen-based fuels is that the nitrogen present in the atmosphere can be used as feedstock. The nitrogen is currently obtained through either cryogenic air separation or pressure swing adsorption. Both methods usually use fossil fuels such as natural gas, fuel oil, and naphtha as feedstock to create the right pressure and temperature. However, both methods can operate on electricity without difficulty and can be integrated into the green ammonia production cycle [101]. Ammonia synthesis is, in general, more flexible regarding the energy type used for its production. For the Haber–Bosch process, the switch from fossil fuels to electricity will reduce emissions by approximately one-third. So, to reduce greenhouse gas emissions, NH_3 must be produced from renewable hydrogen. In the Haber-Bosch process, renewable hydrogen produced via water electrolysis from renewable power can also be used. The combination of water electrolysis and the Haber-Bosch process is called power-to-ammonia (P2A) technology [101].

NH_3 production represents the most energy-intensive chemical commodity, responsible for 1–2% of global energy consumption. Furthermore, ammonia produced conventionally through steam reforming, air separation, and the Haber–Bosch process can directly cause 1.44% of global CO_2 emissions [102]. Therefore, the implementation of an ammonia production method not based on hydrocarbons and so, without emitting CO_2 could contribute for the decarbonisation of an energy-intensive chemical product.

Green ammonia is produced entirely from renewable electricity, air, and water, and so the CO_2 footprint is assumed to be zero, not considering the full cycle, which should include plant construction and transport. Initial estimations of emission reduction for green ammonia are >90% for wind power-based ammonia and >75% for photovoltaic-based ammonia. Another option is hybrid green ammonia, which is produced in hybrid plants that are partially powered by fossil fuel and partially by renewable electricity. This process can be installed through a renovation of an existing conventional plant. Therefore, it is considered an economically feasible transition to green ammonia production. The ammonia production model that makes sense to follow comprises four components: electrolysis, intermediate hydrogen buffer, air separation and ammonia synthesis [103].

Regarding using NH_3 as fuel, it can be combusted in fuel cells (directly in solid oxide fuel cells), engines, or gas turbines. Another possibility is the decomposition of NH_3 by catalytic cracking or the sodium-amide process with the production of hydrogen that can then be combusted in fuel cells or gas turbines. The main interest in ammonia as fuel is replacing fossil fuels in the marine transport sector.

To replace 30% of the current marine fuel with ammonia the scaling up of the production process is needed. The increase of production capacity can be achieved in two ways:

1. Revamping existing plants into hybrid plants based on sustainable hydrogen production by

renewable energy and electrolysers. In that sense, the plants selected for hybrid revamping should be in areas with high penetration of renewable power production to be able to produce green ammonia in periods of high wind and solar generation.

2. Implementing new plants for 100% green ammonia production based on sustainable hydrogen production (renewable energy and electrolysers).

The bottleneck identified in the green ammonia synthesis is the electrolysers' hydrogen production capacity, which is presently relatively low. Therefore, it makes sense to start by revamping existing ammonia plants into hybrid ones by introducing electrolysis capacity and gradually increasing it. The electrolysers' production capacities are already increasing due to the large investment of the electrolyser suppliers, which are making efforts to scale-up the production [104].

3.5.4 Sustainable aviation fuels (SAFs) and other synthetic fuels

Aviation is one of the most difficult to defossilise transportation sectors since the fuel quality must meet strict quality specifications. Bio-based fuels have been proposed as a short to medium-term alternative to fossil jet fuel. Producing SAF on a large scale requires strategies to meet the proposed production targets [105]. However, Sustainable Aviation Fuels (SAFs) produced from renewable electricity via Power-to-Liquids (PtL), also called e-jet fuel, can reduce greenhouse gas emissions of airplanes by up to 90% but are clearly more expensive than fossil jet fuel [106].

According to the REDII directives from the European Union, since January 2021, an alternative fuel can only be considered sustainable if the GHG emissions reduction is at least 65% compared to conventional fuel, which emits 89 gCO_2/MJ [107]. In this directive, SAF produced by green electricity is considered not only sustainable but also Renewable Fuels of Non-Biological Origin (RFNBOs). One definition for the renewable liquid and gaseous transport fuels of non-biological origin is "liquid or gaseous fuels which are used in the transport sector other than biofuels or biogases, [whose] the energy source content of which is derived from renewable sources other than biomass" [107].

Power-to-Sustainable Aviation Fuel (Power-to-liquids or PtL) involves the catalytic conversion of green hydrogen and carbon dioxide/carbon monoxide to produce SAF. Despite having the potential to offer the highest greenhouse gas reduction of the different ASTM-certified technical pathways, PtL is the least technically and commercially ready. In this context, PtL production has been proposed as a promising and scalable alternative SAF production pathway. This process combines CO_2, water, and renewable energy to produce SAF with properties that are similar to those of fossil jet fuel. The power to jet fuel installation can be divided into three main units: i) the hydrogen production unit, ii) CO_2 capture, the Fischer-Tropsch synthesis unit, and iii) the product upgrading part. Hydrocarbon synthesis can be performed through two different pathways: Fischer-Tropsch (FT) synthesis, or methanol to jet fuel; however, the FT process outperforms the methanol pathway since the use of blends containing 50% of FT-derived SAF and 50% of conventional jet fuel is ASTM-certified as drop-in fuel [105].

The PtL concept to produce FT-derived fuels is a relatively new alternative pathway, although FT synthesis is an already well-developed technology. The FT process is a mature and reliable pathway for hydrocarbon synthesis, with a wide spectrum of technological options and high plant efficiency extending to more than 80% of e-kerosene selectivity [107]. The

Fischer-Tropsch synthesis allows the transformation of a synthesis gas (CO and H_2) into a mixture of hydrocarbons. It is currently mainly used to transform natural gas into more commercially attractive crude.

A power-to-liquid unit could produce different fuel fractions [107]:

- LPG (bp<30°C; C1 – C4);
- Naphtha (30 <bp <205°C; C4 – C12) - mostly paraffinic and thus produces gasoline with low RON and MON numbers.
- Kerosene (180<bp <280°C; C9 – C18) - feedstock for jet fuel. Due to its low sulphur and high paraffinic content, FT kerosene could be directly used as jet fuel without additional unit.
- Gas oil, Vacuum gas oil and residue (waxes) (>121°C; C16 – C75+) - all these fractions are solid at normal temperature and pressure due to their high paraffinic content. This fraction is called waxes and can be upgraded in a hydrocracker. Heavy fuel oil and diesel could be used in heavy transport and maritime transport, although SNG, ammonia or methanol seem to be more suitable as e-fuel for this sector.

The crude from the FT synthesis cannot be applied directly in aviation, it is necessary to meet the standards of the ASTM relating to jet fuels. To reach specification for jet fuel, the FT liquids need to be distilled into individual fractions such as kerosene, diesel, gasoline or naphtha. For that, a fractional distillation column based on the difference of components' volatility is used [107].

Currently, the most interesting FT products are Kerosene and Naphtha, as they present the most encouraging options for applying FT e-fuel. All other byproducts are effectively recycled to maximise the yield of these two products.

4 Deploying offshore wind P2X in Portugal

This section provides insights to identify strategic locations onshore, close to the coast, to support and develop offshore wind P2X. The section addresses identifying and mapping potential "X" consumers, supply chain, current and planned relevant infrastructure, and relevant ongoing or planned projects.

4.1 Bringing offshore wind power to shore

At this stage, the exact locations where offshore power will be brought to shore are unknown. Table 4.1 shows the first delineated areas for commercial projects that would accommodate about 9.4 GW of offshore wind capacity.

The three areas that would be awarded in the first auctions are located in Viana do Castelo (about 1 GW), Leixões (500 MW), and Figueira da Foz (2 GW). The remaining capacity should be allocated in subsequent phases for a total of 9.4 GW. The existing area off Aguçadoura (off the coast of Póvoa do Varzim) is currently used to demonstrate offshore renewable energy projects and technologies, especially offshore wind.

Table 4.1: Areas identified for offshore wind development and respective power to be installed (GW).

Designated area	**Surface area [km^2]**	**Estimated Power [GW]**
Viana do Castelo	229	0.8
Leixões	722	2.5
Figueira da Foz	1325	4.6
Sines	430	1.5
Aguçadoura	5.6	Not for commercial concessions
Total	2711.6	9.4

Figure 4.1 shows the existing electric substations located within 25 km from the coast (blue circles), potential electrical grid connection points (green circles), as well as the transmission network. The most relevant connection points are those closer to the approved areas, namely Viana do Castelo North, Viana do Castelo South, Leixões, Figueira da Foz, Ericeira and Sines South.

It is relevant to mention that currently, the transmission power grid has limited capacity to integrate new large-scale power generation projects (such as offshore grid power plants). Grid expansion plans are under development to overcome this substantial bottleneck. In this report, the current power grid constraints are not considered.

4.2 Power-purchase agreements and wind offshore in Portugal

Power purchase agreements (PPAs) are contractual agreements between energy buyers and sellers to trade an amount of energy, typically generated by a renewable asset, for a long period (e.g., 10-20 years). PPAs have become popular in recent years. This is because most governments moved away from subsidy schemes (e.g., feed-in-tariffs or feed-in-premiums), and many renewable producers shifted from subsidised projects to open markets, which has increased their risk and affected their revenue. This, in turn, has affected new renewable energy projects. PPAs enable the sale of a portion of the energy to be generated by a new project over the long term to an energy buyer. This will provide security that the new project will bring a return on investment in the future, with smaller uncertainties regarding expected revenues.

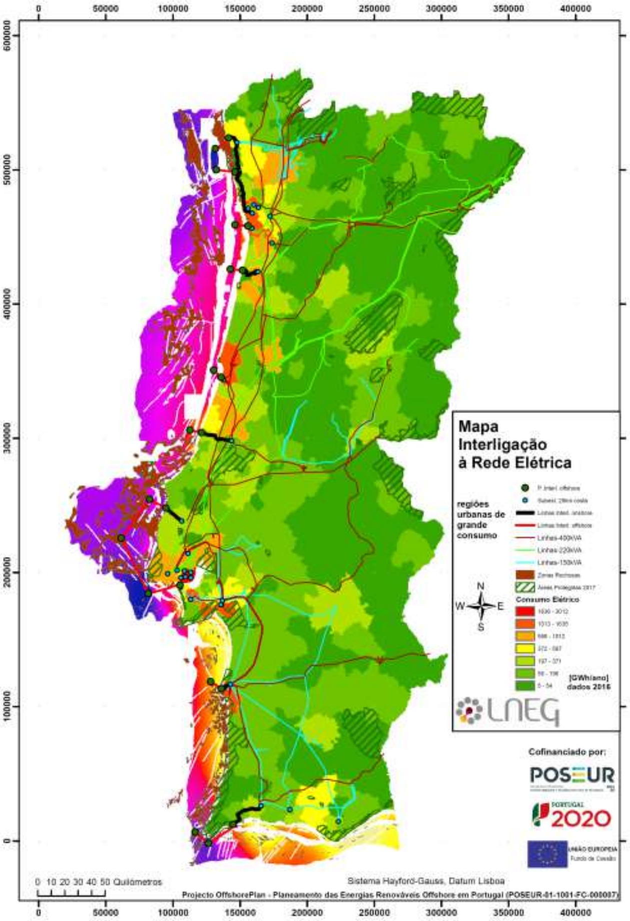


Figure 4.1: Current onshore power transmission connection points potentially relevant for offshore wind power connections with the terrestrial power grid. Source: LNEG.

PPAs are often classified as physical or virtual. Physical PPAs are the traditional form of renewable energy purchasing transactions, involving a physical energy transfer. Typically, the energy is purchased at the reception point of production (meter point), and the PPA customer receives it through the existing transmission lines. The energy traded under physical PPAs may be sent to the day-ahead market (e.g., as positions at minimal limit price), contributing to fossil fuels phase-out. By contrast, virtual or financial PPAs are financial contracts only. Such contracts could be encouraged as an alternative to physical PPAs where direct retail sales are not permitted, or where behind-the-meter generation is not an optimal solution.

PPAs work essentially as follows. The process starts with a new renewable project to be built, involving a location, size, pre-agreed connection to the grid, and so on, or with an existing project that needs refinancing. The project owner goes through a request for proposals and interested energy buyers make offers of purchase. For large established buyers (e.g., Google), this step may involve a private tender or auction, where buyers invite pre-selected parties to bid against each other in several rounds. Next, the parties may initiate a process of negotiation involving several different issues, including the price for the energy produced during the upcoming years, as well as the type and structure of the PPA, the energy risk, and contract termination conditions. After reaching an agreement, they sign the PPA contract. This is typically done before starting a new renewable energy project. It provides a certain level of confidence in the new project since there is a buyer's commitment to pay a fixed price for a long-term tenor for the electricity that will be generated by the renewable asset. Third-party funding sources, such as banks often require this level of confidence.

Generally, PPAs benefit renewable assets, buyers, and credit providers. For renewable assets, PPAs allow the financing of their projects by lenders and reduce the inherent risk by efficiently allocating it between the contractual parties. For buyers, PPAs assure fixed long-term costs and allow them to fund renewable projects (receiving, e.g., Renewable Energy Certificates). For credit providers, PPAs increase their revenue certainty since an amount of energy is sold in advance at an agreed price and enable them to claim their contribution to the renewable industry.

4.2.1 Offshore wind power via PPAs for industrial consumption

Annual average electricity consumption in industry per municipality in mainland Portugal was obtained using the land occupation data (municipalities' borders) provided in [108] and the consumption of electricity in those municipalities, which data were produced by the General Directorate of Energy and Geology (DGEG).

Table 4.2: Overview of annual average industry power consumption per municipality in Portugal in GWh.

Municipality	**Annual average consumption (GWh)**
Figueira da Foz	1 210.40
Sines	1 020.26
Setúbal	964.56
Maia	827.22
Seixal	747.05
Estarreja	578.22
Vila Nova de Famalicão	519.18
Aveiro	468.66
Marinha Grande	418.8
Vila Franca de Xira	416.91
Guimarães	349.87
Viana do Castelo	349.59
Santa Maria da Feira	302.46
Matosinhos	300.75
Vila Nova de Gaia	286.59
Leiria	271.94
Santo Tirso	258.28
Palmela	252.52
Vila Velha de Rodão	234.93
Oliveira de Azeméis	214.69

Within the municipalities with the highest power consumption in mainland Portugal, 16 existing specific industries or industry parks identified could be potential prime consumers of electricity from offshore wind. For more information regarding the annual consumption of industrial areas, consult the technical report in Ref. [109].

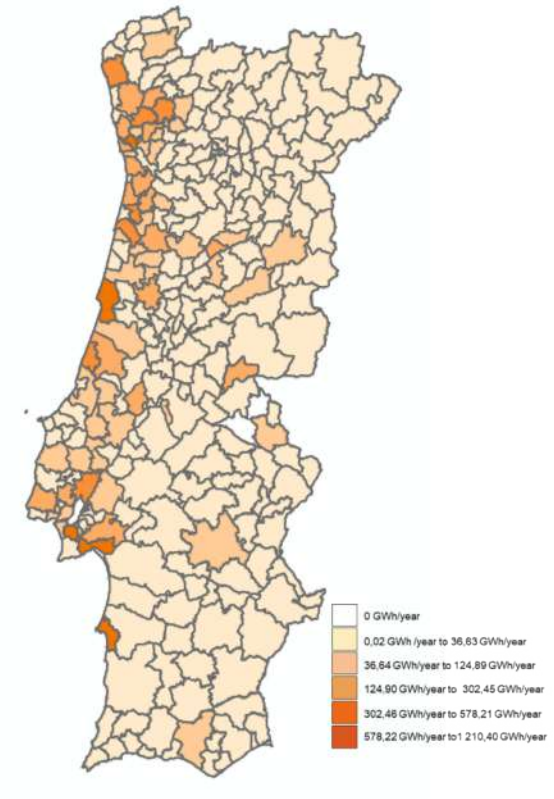


Figure 4.2: Overview industry power consumption per municipality in GWh - Annual average 2016, 2017, 2018, 2019, 2021. Data collected from [7].

4.3 Potential hydrogen consumers

Using the publicly available information on PRTR [110, 111] as the main data source, a list of circa 111 potential industrial H_2 consumers was prepared and updated with 2018 data. These potential consumers locations were defined based on their main industry activity for each "industry plant", considering the activity classification as in the activity categories of IPPC – Integrated Pollution and Prevention Control legislation.

4.3.1 Current potential H_2 consumers: Transport sector

The following potential hydrogen consumers from the transport sector were identified:

- 121 locations that refer to passenger transport companies' road interfaces and terminals in based on own information and data supplied by Portuguese Institute for Mobility and Transport (IMT);
- 60 locations that refer to freight transport companies are located along the main routes for both national and international freight transport, namely highways A1, A6 and A25.

Table 4.3: Overview of current industries that could become hydrogen consumers as a replacement for natural gas.

Type of potential consumer	No. of plants / locations
Energy Production/Refineries	10
Chemical	36
Cement and Lime	11
Glass	7
Ceramic	22
Pulp and paper	25
Total	111

> This information was supplied by ANTRAM - National Association of Public Road Freight Transporters (Associação Nacional de Transportadores Públicos Rodoviários de Mercadorias). The locations represent the entry points into these highways.

Besides consuming H_2 as an energy vector, some industry activities consume H_2 as a feedstock in their productive process. These were compiled representing ten plants and are represented in Figure 4.3 and Table 4.4.

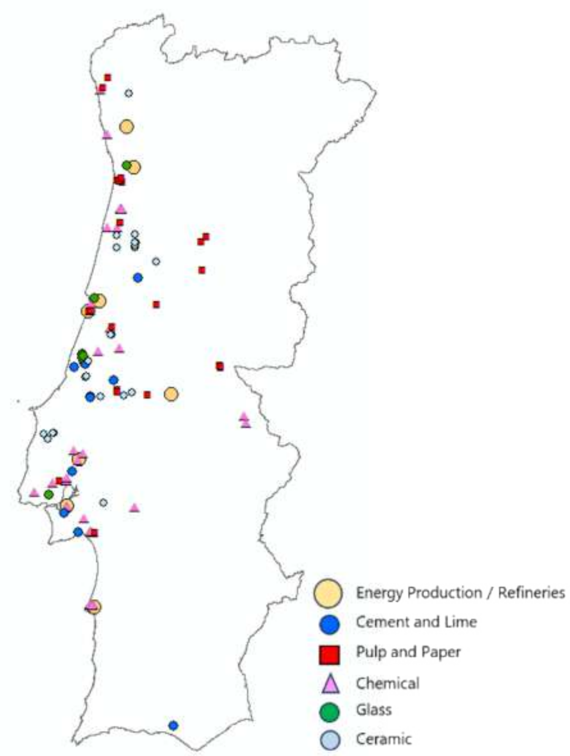


Figure 4.3: Current potential industry H_2 consumers. Source: LNEG over PRTR Database, and own information.

4.4 Portugal and P2X technology supply chains

A database of companies for offshore wind and other offshore renewables was created within the OceanTrans Project (`https://www.oceantrans.info/`), and a summary is presented in

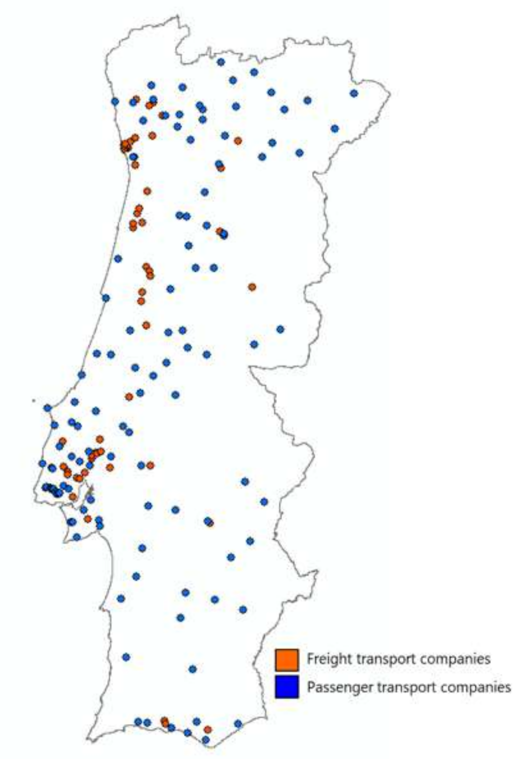


Figure 4.4: Current potential transport H_2 consumers. Source: LNEG Sustainable Green H_2 Atlas [8].

Table 4.4: Overview of current industries that consume hydrogen as a feedstock.

Company	Activity
Sociedade Portuguesa do Ar Líquido ”ARLIQUIDO”, LDA-CPE	Chemical
ADP Fertilizantes S.A - Unidade Fabril do Lavradio	Chemical
Omya S.A.	Chemical
Hychem - Complexo Fabril da Póvoa de Santa Iria	Chemical
Specialty Minerals Portugal, Especialidades Minerais, S.A.	Chemical
ADP -Fertilizantes, S.A.	Chemical
Sopac - Sociedade Produtora de Adubos Compostos, S.A.	Chemical
Refinaria de Sines	Refineries/Energy Production
Bondalti Chemicals, S.A.	Chemical
Indorama Ventures Portugal PTA (Fábrica de PTA)	Chemical

Table 4.5. The database was a product of a consultation with more than 500 companies in Portugal, from which the interest or capabilities for the intervention in the offshore wind supply chain and other offshore renewables were collected and then translated into a public database (`https://www.oceantrans.info/directorio-de-empresas`). The database has been updated since the end of the project, and Table 4.5 reflects current data. It can be seen that at least 127 companies in the different categories have Portuguese origins, while at least 14 are subsidiaries of foreign companies. Please note that when stated ”at least”, it is due to the fact that there might be more that have not been mapped yet. The study is based on the consultation of a number of companies selected by their economic activity codes and internal knowledge of companies that have acted in the offshore energy sector, and it does not represent an exhaustive identification

of companies. It is also worth mentioning that not all the companies consulted answered the survey designed within the OceanTrans project.

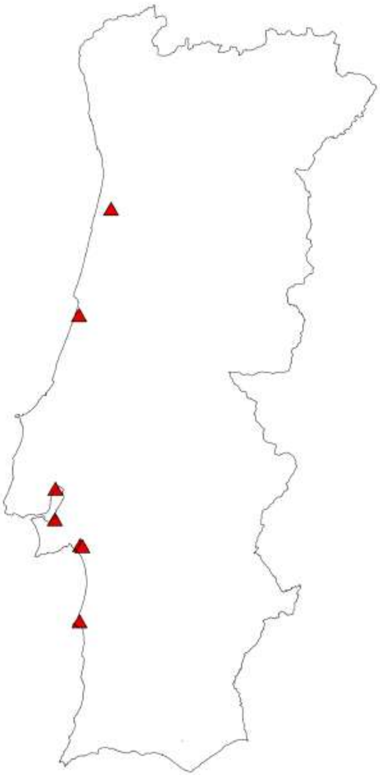


Figure 4.5: Current potential industry consumers of H_2 as a feedstock. Source: LNEG (over PRTR and own information).

More recently, another database of companies for green hydrogen and other renewable fuels was created and includes companies that have been monitored over the last year and that are of public knowledge, their membership in associations, CoLabs, and other past, planned, or active projects in Portugal (see Table 4.6). In this case, no consultation with companies has yet been done, unlike for the offshore wind and other renewables database. This is an activity planned for the near future.

The supply chain companies database has been classified into seven categories defined as follows:

- Project developers: This category groups companies that build, own and operate hydrogen and sustainable fuel infrastructures (and related processes) and offshore renewable energy.
- Advisory service providers: Companies that advise project developers and owners on both the high-level project feasibility, market engagement approach in relation to EPCs, and finally evaluate the offered plant designs from technology providers.
- R&D: Research and development organisations, not considering universities or their directly linked research centres. Most of the R&D organisations are Colabs and private companies' related R&D branches.
- Technology providers: Companies that can provide goods and / or services in different stages of the value chain of the targeted sectors. These companies typically hold various

technology patents or highly differentiated goods and services.

- Engineering, Procurement, and Construction (EPC): Companies that specialise in detailed engineering, procurement and construction execution.
- Original Equipment Manufacturers (OEM): Companies that manufacture and supply main physical equipment (hardware) to EPCs for the construction of offshore wind or hydrogen and renewable fuels infrastructure.
- Operation & Maintenance and general service providers (e.g. logistics): Companies that perform a physical or digital service, e.g. logistics and other infrastructure-related services, digital twins.

Table 4.5: Summary of offshore wind and other offshore renewables supply chain companies in Portugal.

Offshore Wind & Offshore Renewables	**Project Developers**	**Advisory**	**R&D**	**Technology Providers**	**EPCs**	**O&M**	**OEMs**	**Total**
Portuguese Companies	8	19	9	47	15	19	10	127
Foreign Mother Companies	4	3		4	2		1	14
Total	12	22	9	51	17	19	11	141

Table 4.6: Summary of hydrogen and other renewable fuels supply chain companies in Portugal.

Hydrogen & Renewable Fuels	**Project Developers**	**Advisory**	**R&D**	**Technology Providers**	**EPCs**	**O&M**	**OEMs**	**Total**
Portuguese Companies	25	15	11	31	10	8	4	104
Foreign Mother Companies	9	4	0	11	0	0	1	25
Total	34	19	11	42	10	8	5	129

4.5 Relevant on-going P2X initiatives in Portugal

In Portugal, several projects are being developed to produce green H_2, which is essential in industrial sectors such as refineries and fertilisers, as well as potential sectors like transport. The hydrogen produced is expected to be used for several different applications, including injection into the natural gas distribution network, as an input in the production of green ammonia, aniline production, to export (eventually to Spain), as well as bottling in pressurised cylinders for industrial uses. The projects are located throughout the country, concentrating more on regions near the coast (for example, Sines, Setúbal, Marinha Grande, and Nazaré). Some of the projects are part of Mobilising Agenda programs (Agendas Mobilizadoras), such as H_2 Green Valley, Sines Green Hydrogen Valley (SinesH_2GValley), Moving2Neutrality, and H_2DRIVEN. A list of some important projects in different phases of their life cycle is presented in the following table. Most of these projects are part of the endeavour to achieve the PNEC 2030 revised in 2024, with a target of 3 GW of electrolysers for green hydrogen production by 2030.

Considering the projects that are being developed to produce green Hydrogen in Portugal, some of them are listed in Table 4.7, three of them will be described in more detail below, as they are not only projects to produce green Hydrogen but also include the (i) transport of green hydrogen, the (ii) production of ammonia, and the (iii) production of green methanol.

(i) Regarding the production and transport of green hydrogen, there is a particularly challenging large-scale project, involving Portugal, that will require a large quantity of electricity to work. This is the H_2Med/CelZa Project which includes two transboundary interconnections, and consists of building two pipelines, allowing to transfer hydrogen from the Iberian Peninsula to France. The first pipeline would connect Celorico, Portugal, to Zamora, Spain, (H_2Med-CelZa project), extending over 250 kilometres. It will connect Portugal's hydrogen production to the port city of Barcelona via Spain‘s emerging main transport axes.

    The second pipeline would be a submarine interconnection between Spain and France (H_2Med-BarMar project). This would be a much more complex and expensive, pipeline that will be built to run from the Catalonian coast and transmit gas from the Iberian Peninsula to Marseille, France. The BarMar project will be nearly twice as long as CelZa, extending over some 450 kilometres. The pipeline will rest on the Mediterranean seabed, at depths of up to 2 600 metres. Then, the hydrogen will flow from the port city in the south of France to major European industrial regions. Germany also will join this pipeline project. H_2Med will have the capacity to transport up to 2 million tonnes per year (Mtpa) of renewable hydrogen, which represents 10% of the forecast consumption in the European Union, according to REPowerEU.

(ii) Considering the production of ammonia, the MadoquaPower2X is a green hydrogen and ammonia project in Portugal that will use renewable energy and 500 MW of electrolysis capacity to produce 50,000 tons of green hydrogen and 500,000 tons of green ammonia on a large scale annually. It is the first project to be installed in the future energy and technology hub of Sines on an industrial scale. The hydrogen produced under this project can be used by the local industry as well as processed to create green ammonia for export from the terminal at the port of Sines. Electricity will be sourced from renewable power produced in Portugal, from renewable energy communities for wind and solar plants that are being developed in parallel. This approach will ensure the availability of dedicated renewable energy throughout the project's lifetime. MadoquaPower2X is a consortium comprising Madoqua Renewables, Power2X, and Copenhagen Infrastructure Partners (CIP).

(iii) Considering the production of green methanol, the H_2Driven Green Agenda is the name of the consortium led by Efacec Engenharia e Sistemas, together with seven industrial partners: Dourogás Renovável, The Navigator Company, Bondalti Chemicals, Capwatt, Sonae Arauco Portugal, Administration of the Ports of Douro, Leixões and Viana do Castelo, and Compatibleglobe (from the Lightsource BP group). In addition, it has two small and medium-sized companies, Amnis Pura and Seamoretec, as well as the Faculty of Engineering of the University of Porto and the Collaborative Laboratory for Biorefineries. H_2Driven foresees the creation of up to three green methanol plants. The number of factories depends on their size. This biofuel contains green hydrogen and carbon dioxide (CO_2) from biomass plants. Therefore, the factories to be built would have to be close to biomass plants, from which CO_2 would be used, and would involve the installation of electrolysers to produce green hydrogen (with electricity from renewable sources).

    This biofuel is used mainly in two large-scale areas of activity: the production of fertilisers and glues for wooden boards. The consortium intends to replace methanol, now of fossil origin, with green methanol, contributing to the decarbonisation of the industry, with the hypothesis being considered that green methanol could also be used as fuel in maritime transport.

The national consumption of green methanol in Portugal is currently around 150 thousand tonnes annually. The proposal foresees the production of 200 thousand tonnes per year and is already planning to export; the project is expected to start in 2025.

The green hydrogen used to produce green methanol could also be injected into the natural gas network or to fill stations for trucks powered by this fuel, although this is not the project's focus.

Figure 4.6: H_2MED project pipeline network overview. Reproduced from [9]. Original source: Spanish Ministry of the Environment.

Figure 4.7: MadoquaPower2X project. Reproduced from [10].

Table 4.7: List of selected green hydrogen projects by municipality and their description.

Municipality	Project Name	Description
Águeda	H_2 Production Unit - Referência Fluorescente	Company: Referência Fluorescente, Lda. Development of a green H_2 production plant to supply the ceramics sector. In electrolysis, will be used electricity obtained from the public grid with a certified renewable. Surplus renewable H_2 will be made available to other industry sectors in the region, heavy transport vehicles, local autonomous natural gas network, or light vehicle fleets.
Alenquer	FLEXnCONFU	Company: EDP - Gestão da Produção de Energia, S.A. FLEXnCONFU is a European innovation project funded by the Horizon 2020 program. Launched in April 2020, which aims to develop and integrate new solutions to increase the flexibility of combined cycle power plants through the integration of unconventional fuels (e.g., hydrogen and ammonia) to test the compatibility and efficiency of combustion systems and new solutions for the energy transition. EDP's first hydrogen molecule was produced in Europe using a 1.25 MW Cummins PEM electrolyser, the largest in the country. 1% of H_2 will be injected upstream of the gas turbine in Group 2 of the Ribatejo CCGT.
	H_2Mobility Alenquer	Company: EDP - Gestão da Produção de Energia, S.A. Implementation of a pilot unit for decentralised production of green H_2 with PEM technology aimed at industrial clusters, including P2G technology with injection of green H_2 into the national natural gas network, distribution, and consumption for a Hydrogen Refueling Station (HRS) filling station. The project will be carried out in the municipality of Alenquer and the unit will be installed in the industrial perimeter of a thermal power plant. HRS supply to Heavy-Duty Vehicles (HDV) part of the project is currently suspended.
Alter do Chão	PTSUNH_2 - Hydrogen production unit	Company: PTSUNHYDROGEN, Lda and the involvement of Dourogás Natural S.A. The project aims at developing an integrated system of hydrogen production of 10 MW, storage, transport, and injection into the SNG of green H_2, with additionally considered the transport of hydrogen in the gaseous, compressed phase, to end users, such as industrial customers or vehicle fuel stations, covering an extended value chain (from production to the final consumer).
Castelo Branco	Monte Das Areias Green Hydrogen Production Plant – CHV	Company: EWE CB H2, Unipessoal Lda. Production of green H_2 through the electrolysis process, generated by an electrolyser, which in turn will be powered by 100% renewable and non-polluting electrical energy (solar and wind).

Municipality	Project Name	Description
Celorico da Beira	H_2MED/CelZa	The CelZA project will connect Portugal and Spain to France and at a later stage to Germany. The project involves building two pipelines, one is the CelZa connecting Celorico, Portugal, to Zamora, Spain, and will transport Portugal's hydrogen production to the port city of Barcelona via Spain‘s main transport axes. The second (Dubbed BarMar) pipeline will be built to run from the Catalonian coast and transmit gas from the Iberian Peninsula to Marseilles, France. This project will be more detailed below.
Estarreja	H_2Enable	Development of an infrastructure for the production of green H_2 in the Estarreja Industrial complex, for self-supply in the production of aniline, injection into the national natural gas network, and for the mobility sector.
Leiria	Nazaré Green Hydrogen Valley	Company: REGA ENERGY (consortium composed of 13 entities). Installation of a green Hydrogen and Oxygen production unit, through water electrolysis with an installed capacity of 40 MW, using energy from renewable sources, in Marinha Grande. The objective is to help and support the local cement and glass industries in decarbonization processes, which due to the characteristics of their processes cannot be fully electrified, which leads to the need to replace natural gas and petcoke with renewable alternatives such as green hydrogen.
Nazaré		
Alcobaça		
Marinha Grande		
Marinha Grande	H_2 Global - Production, Storage and Supply of green H_2 in a strategic environmental assessment	Company: CME - Construção e Manutenção Eletromecânica, SA. It aims to implement a green hydrogen production unit, using PEM technology, close to an industrial area with several potential sectors using hydrogen for its decarbonization (example: Gallo Vidro, S.A.). Associated with the production and distribution unit, there will also be a unit for supplying heavy vehicles and transporting goods or passengers, to make it possible to evaluate the use of hydrogen in the industrial and mobility sector, based on different requirements.
Mangualde	H_2DRIVEN Green Agenda	Company: EFACEC ENGENHARIA E SISTEMAS, S.A. (consortium composed of 17 entities). H_2DRIVEN aims to implement a new value chain around green electro-fuels in Portugal, with the capacity for the design, development, and production of green H_2, biogenic CO_2, and electro-methanol. This project will be more detailed below.
Oliveira do Bairro	Aveiro Green H_2 Valley	Company: Smartenergy. The project consists of an electrolyser that will produce green H_2 (5700 t.p.a.) in Oliveira do Bairro (COD end of 2025). Focused on Power to Industry, Gas grid Injection, and Power to Mobility. Electricity is sourced from a PV plant in Aveiro District (170 MWp).
	Cluster H_2 Oliveira do Bairro	Company: WP2X, Lda. Construction of a green H_2 production unit, to supply an Industrial unit in Oliveira do Bairro and injection of the surplus into the National Gas System (SNG) network.

Municipality	Project Name	Description
Pombal	Renewable gas production unit: Industrial self-consumption and injection into the distribution network	Company: ALÍNEA GRATIFICANTE UNIPESSOAL LDA. In situ installation of an electrochemical process (electrolysis) to produce renewable gases (H_2 and O_2) for self-consumption in the manufacturing unit, replacing the Natural Gas used in the various equipment in the production process (atomizers, ovens, dryers), injecting them into the internal distribution network(s).
Rio Maior	Cluster H_2 Rio Maior	Company: Marte Boémio, Unipessoal, Lda. Production of hydrogen by PEM electrolysis using electricity from a dedicated photovoltaic plant and the grid (with Guarantee of Origin); compression, storage, and injection in the National Gas System (SNG), at JTC do Alto da Serra, owned by REN, the concessionaire of RNTG (National Gas Transport Network), with possible use in several natural gas consuming industries existing in the Rio Maior region.
Seia	Hydrogen Production Plant Installation Project in Seia	Company: HEN - Serviços Energéticos, Lda. Implementation of a green H_2 production plant, which will allow the injection of renewable gas into the natural gas network, as well as the distribution of H_2 to two filling stations, located in Guarda and Albergaria-a-Velha. At these stations, H_2 will be used to fuel vehicles and will be the fuel used in the fuel cell, to allow the charging of electric vehicles.
Setúbal	Hyperion H_2 Setúbal	Company: Hyperion Renewables H_2 Unipessoal, LDA. The HPU will be next to a solar PV facility with a 12 MW output capacity. A renewable PPA will also be constructed to increase the load factor of the electrolysers and boost output. Will produce 135 kg of green hydrogen, or 1500 Nm^3, every hour. One destination will be the selling of compressed hydrogen at roughly 200-300 bars to off-takers who would load tube trailers on-site. The Portuguese natural gas distribution system will be its second stop. Between the production unit and the network injection point, a pipeline will be constructed, and hydrogen will be pumped at a pressure of 20 bar.
	M-ECO2	Company: PRIO BIO S.A. (consortium composed of 15 entities). Development of an industrial cluster to produce advanced sustainable biofuels based on green H_2 and waste raw materials. The project focuses on the implementation and operation of a new industrial unit in the Port of Setúbal, which will include the production of energy from renewable sources (solar and wind), green H_2, and advanced biofuels.
Alandroal	Hyperion H_2 Alandroal	Company: Hyperion Renewables H_2 Unipessoal, LDA. Construction of a plant whose power capacity can range from 100 megawatts (MW) to 250 MW of electrolyser, to produce green H_2, via renewable electricity. The company wants a solar plant with 250MW and a wind plant with a capacity of 100MW. The objective is to export hydrogen via rail transport, either to Spain or to other countries via the port of Sines. The company is working in a strategic consortium with relevant companies in the sector.

Municipality	Project Name	Description
Sines	GreenH_2Atlantic	Company: Consortium composed of 13 entities. The 100 MW alkaline electrolyser will be composed of innovative, scalable, and fast-cycling 16 MW modules to overcome bottlenecks such as efficiency, size, lifetime, and flexibility. Other innovative features include an interface system composed of an Advanced Management System to ensure a reliable supply of H_2 to the off-takers and enable the project's coupling to a local hybrid renewable power plant (solar and wind). GreenH_2Atlantic will enable the transition of a former coal-fired power plant into an innovative renewable hydrogen production hub.
	NeoGreen	Business collaboration between NeoGreen Hydrogen Corp (Canada) and the Portuguese Frequent Summer S. A., for the installation of an electrolyser complex of more than 500MW. The production unit for green hydrogen and derived fuels will be located in the Sines Industrial and Logistics Zone (ZILS).
	MadoquaPower2X	Company: Consortium composed of Madoqua Renewables, Power2X, and Copenhagen Infrastructure Partners (CIP). MadoquaPower2X will use renewable energy and 500 MW of electrolysis capacity to produce 50000 tons of green hydrogen and 500000 tons of green ammonia on a large scale annually.
	Moving2Neutrality	Company: PETROGAL, S.A. (consortium composed of 13 entities). The Moving2Neutrality Agenda responds to the challenge of the energy transition in transport by producing sustainable fuels towards carbon neutrality. Led by Petrogal, the consortium is based at the Green Energy Park in Sines, taking advantage of the region's unique endogenous conditions to become a green energy production hub. It intends to produce green H_2 on an industrial scale, produce green fuels for transport, distribute green H_2 to the road sector, and develop 13 projects promoting the creation of knowledge clusters in low-carbon technologies.
	H_2 Green Valley	Company: REN, GÁS, S.A. (consortium composed of 8 entities). Development of a green H_2 transmission infrastructure, an injection and mixing system in the gas network, the adaptation of the Sines gas distribution network, and development of equipment to implement a pilot conversion of domestic consumers to H_2, as a demonstrator for a 100% green future.
	GalpH_2Park	Company: GALP. The GalpH_2Park for Green Hydrogen Production and Storage will have a capacity of 100 megawatts and will be installed in the Sines Industrial and Logistics Zone (ZILS). The hydrogen produced will be consumed by the refinery itself to replace the gray hydrogen, produced from fossil fuels, already consumed in the complex. Installation of 100 MW unit for hydrogen production by 2025. By 2026, the project is expected to expand up to 600 MW, to guarantee the complete replacement of gray hydrogen with green hydrogen in the Sines Refinery activity. Finally, by 2030, capacity expansion is planned to reach 1.5 GW. This increase in capacity will serve to meet renewable hydrogen needs for low or zero-carbon fuel production projects, particularly for aviation and the maritime sector.

Municipality	Project Name	Description
Vila Franca de Xira	Galileu Green H_2 Valley	Company: Smartenergy. The project consists, in the first phase of a 125 MW El that will produce green H_2. Electricity is sourced from 400 MWp of solar PV in the same area and from renewable energy PPAs. The second phase consists of a 235 MW El. The project focused on Power to Industry (cement plant), Gas grid Injection, and Power to Mobility. Advanced talks with value chain partners, e.g., for offtake, pipeline construction, and H_2 transport.
	H_2Hub	Company: HYCHEM, QUÍMICA SUSTENTÁVEL, S.A. Development of a platform for green H_2 production technologies. It envisages the reinforcement of H_2 production capacity, through the installation of a steam reformer powered by biomethane and an alkaline electrolyser, and the increase in high-pressure storage capacity in bottles. The investment to be made will allow the injection of H_2 into the natural gas network, through a compression station, connection, and mixing piping in Frielas, supplying the north bank of the Lisbon metropolitan area, as well as opening new perspectives for mobility.
Vila Velha de Rodão	H_2 Solar - Green hydrogen production unit	Company: CME - Construção e Manutenção Eletromecânica, SA. Green hydrogen production unit, close to an industrial unit in Vila Velha de Ródão, which is dedicated to the manufacture of paper and cardboard, (Paper Prime, S.A.), in which a percentage of green hydrogen will be introduced into its processes.

4.6 Water supply for hydrogen production

Regarding the location of potential water sources for hydrogen production in Portugal, two main sources are mapped in this report: wastewater from wastewater treatment plants (WWTP) and seawater. For WWTP, with a capacity of 10000 pe (population equivalent), could provide a minimum flow of 1000 m^3/day to ensure not only the amount of water for feeding the electrolyser, but also the need for additional treatment to reach the admissible water quality level for electrolysis. The adopted criterion was the distance of the WWTP with a minimum capacity of 10000 pe.

Figure 4.8 illustrates the existing wastewater treatment plants in Portugal's mainland with the capacity to serve at least 10000 pe, the port areas which include marinas and fishing docks, sea and river port terminals and shipyards and dry docks, as well as the coastal beaches areas along the coast of Portugal. All these locations are indicated since they are areas to be considered when potentially defining seawater collection sites for desalination.

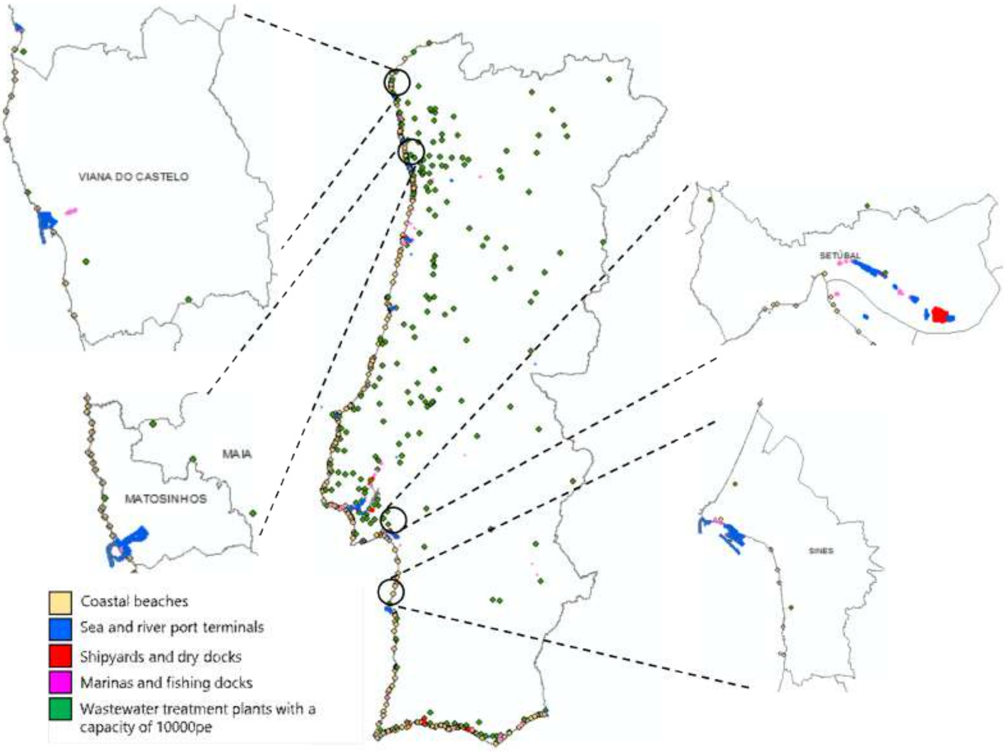


Figure 4.8: Location of relevant sources of wastewater and of ports, harbours, marinas, and bathing areas, all of which should be considered for assessing future locations for seawater collection sites for desalination. Source: LNEG.

5 Techno-economic comparison of offshore wind P2X options

This section presents the evaluation of seven scenarios, representing different options of P2X from offshore wind. The methodology, the techno-economic parameters used, and the results are presented and discussed. Some recommendations are drawn for public and private stakeholders.

5.1 Methodology

The methodology to assess techno-economically various offshore wind P2X options is depicted in Figure 5.1. The methodology involved the selection of one of the offshore planned areas for offshore wind in Portugal and, according to the location of the area and its potential installed capacity, both the location onshore and the capacity of the hydrogen production unit and the sustainable fuels hub were determined. The location considered is the offshore planned area of Leixões, with a potential offshore wind farm capacity of 1 GW, which is expected to be operational by 2035. It is worth mentioning that currently there is a floating wind park of 25 MW operating off the coast of Viana do Castelo. The capacity of the hydrogen production plant was assumed to be 500 MW, and all the electricity generated from the offshore wind would be dedicated to operating the hydrogen and fuels hub. The quantities of sustainable fuel production and their distribution depend on the definition of scenarios. It is important to note that the definition of the wind farm and hydrogen - sustainable fuels production hub are hypothetical case studies, and LNEG must not held responsible for deviations regarding real project numbers. To evaluate techno-economically the different scenarios (or options), techno-economic parameters were collected from various sources. This was followed by the assessment and comparison of the scenarios. The analysis yielded recommendations for both private and public sector stakeholders.

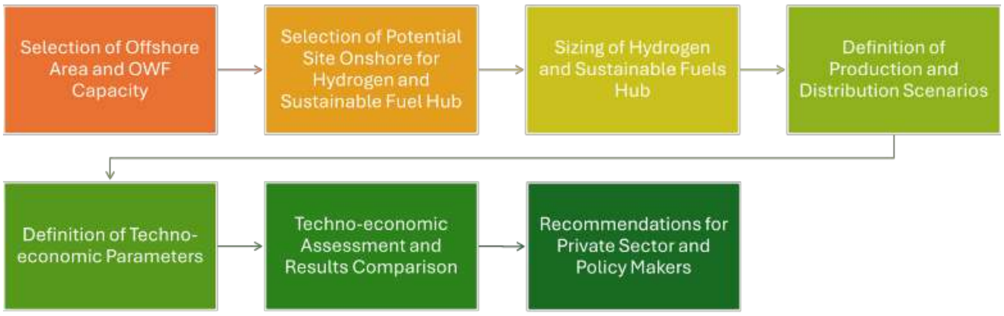


Figure 5.1: Methodology overview for the techno-economic analysis of offshore wind P2X options. Source: LNEG.

Table 5.1 summarises the main characteristics of the location and capacity of the offshore wind farm and the hydrogen production plant.

Table 5.1: Main characteristics of the location and capacity of the offshore wind farm (OWF) and the hydrogen production plant.

Parameter	**Value**	**Unit**
Location of OWF	Leixões (Offshore)	-
OWF Capacity	1000	MW
Location of H_2 Prod. Plant	Industrial/Logistic Area (near) Port of Leixões (Onshore)	-
Electrolysis Plant Capacity	500	MW
Hydrogen Production Capacity	65674	t/year

5.1.1 Scenarios definition

Seven scenarios were defined to assess techno-economically various Power-to-X pathways. The scenarios are shown in Table 5.2. Scenario S1GH2100 refers to the use of gaseous hydrogen as a final product, while S2LH2100 refers to 100% of the production being hydrogen liquified as a commodity to commercialise. Scenarios starting with S3 to S6 involve the production of sustainable fuels or products. This means that the hydrogen produced will be used to produce 100% of one of the following compounds: ammonia (S3AMM100), methanol (S4MET100), HVO (S5HVO100) or SAF (S6SAF100). The last scenario involves the production of various products (liquefied hydrogen, ammonia, methanol, HVO, and SAF) simultaneously, utilising each 20% of the total green hydrogen produced.

Table 5.2: Scenarios considered for this study.

Scenario	**GH2** [%]	**LH2** [%]	**AMM** [%]	**MET** [%]	**HVO** [%]	**SAF** [%]
S1GH2100	100	-	-	-	-	
S2LH2100	-	100	-	-	-	-
S3AMM100	-	-	100	-	-	-
S4MET100	-	-	-	100	-	-
S5HVO100	-	-	-	-	100	-
S6SAF100	-	-	-	-	-	100
S7ALLP20	-	20	20	20	20	20

5.2 Techno-economic parameters

This section presents the technical and economic parameters and assumptions used to assess the scenarios.

5.2.1 Offshore wind costs

Table 5.3 presents the parameters used to determine the LCOE of a 1 GW offshore floating wind farm. The estimate was done by LNEG and represents a farm that is assumed to be operational in 2035. Considering the time for the Engineering & Development, Environmental Impact Assessment (EIA), Licensing, EPC, and Commissioning of the offshore floating wind farm. No fiscal incentives were considered in the estimation of the LCOE.

Table 5.3: Offshore wind farm costs.

Parameter	**Value**	**Units**
CAPEX	3800	€/kW
OPEX	4.5	% CAPEX/year
DECEX	5	% CAPEX
WACC	10	%
Capacity Factor	0.5	-
Farm availability	97	%
Lifetime	30	years
LCOE	135.4	€/MWh

5.2.2 Hydrogen production onshore

The hydrogen production unit is 500 MW and is located onshore near the Port of Leixões. Table 5.4 presents the main parameters of the hydrogen production unit. The water demand is supplied by desalinated water, and Table 5.5 presents the main parameters considered to assess the costs of this water source. The reverse osmosis desalination plant will be located next the hydrogen - sustainable fuels production hub. The load factor of the hydrogen production unit was set to 0.833, which corresponds to about 7300 hours of operational hours at rated capacity. This value is in the high-end interval of a typical water electrolysis plant, but deemed feasible for industrial facilities. When the electricity supplied by the wind farm is not sufficient to cope up with the hydrogen production unit demand, other onshore renewable electricity supply sources were assumed at the same cost, i.e., 135.4 €/MWh. The hydrogen intermediate storage and compression are presented in Table 5.6. It is important to remark that these costs are assumed to be 2035 costs, which will benefit from learning and economies of scale in comparison to current costs. For example, the mean CAPEX of hydrogen production via electrolysis has been estimated in 2406 €/MW of electrolysers in 2024 [112], assuming a learning curve of 90%, the CAPEX in 2035 will be about 750 €/MW of electrolysers, which is aligned with estimations done by Fraunhofer [16, 17] for units starting operations in 2030. However, due to the actual slow pace of development in the water electrolysis production units for green hydrogen production, it is deemed that this level of cost will only be achieved (for units that start operation) in 2035 and not in 2030.

Table 5.4: Green hydrogen production parameters [16–20].

Parameter	**Value**	**Unit**
Technology	PEM electrolysis	-
Rated input power	500	$MW_{AC,input}$
Rated hydrogen production rate	18	$kgH_2/h/MW_{AC,input}$
SEC at rated production	52	kWh/kg
Hydrogen production pressure	30	bar
Lower part load limit	10	%
Water demand	18	l/kgH_2
CAPEX	750	$€/kW_{AC}$
OPEX	15	$€/kW_{AC}/year$
System lifetime	30	years
Stack lifetime	85,000	Operating hours

Table 5.5: Seawater desalination plant parameters [15–17].

Parameter	Value	Unit
Specific energy consumption	3.6	kWh/m^3
CAPEX	1,640	€/(m^3*d)
OPEX	128	€/(m^3*d)/year
Lifetime	30	years

Table 5.6: Hydrogen intermediate storage and compression parameters [15–17, 21, 22].

Parameter	Value	Unit
Total rated mass flow	7.5	t/h
Input pressure	30	bar
Output pressure	80	bar
Number of stages	2	-
Specific Power Consumption	0.4	kWh/kgH$_2$
CAPEX	1,295	€/(kgH$_2$/h)
OPEX	4	% CAPEX/year
Lifetime	30	years

5.2.3 Hydrogen conversion and products

Hydrogen produced in the hydrogen production unit can be used to store and distribute in liquid form (liquefied hydrogen), or to produce ammonia, methanol, HVO, and/or SAF. The different scenarios presented in Table 5.2 consider different production situations that are evaluated in this report. Table 5.7 presents the parameters considered for the liquefaction of hydrogen or production of other sustainable fuels.

Table 5.7: Hydrogen conversion parameters [16, 17].

Parameter	H$_2$ Liquefaction	Ammonia Synthesis	Methanol Synthesis (CO$_2$ based)	Liquid Fuels (Fischer-Tropsch) (CO$_2$ based, incl. RWGS)	Unit
Rated capacity	According to scenarios S2 to S7				
Operating pressure (inlet)	20	250	70	30	bar
Operating temperature (outlet)	-253	550	255	210	°C
SEC	6.78	0.009	0.18	0.303	kWh$_{elec}$/kg prod.
H$_2$ demand	1.017	0.18	0.195	0.48	kgH$_2$/kg prod.
N$_2$ demand	-	0.83	-	-	kgN$_2$/kg prod.
CO$_2$ demand	-	-	1.43	3.056	kgCO$_2$/kg prod.
CAPEX	According to scenarios S2 to S7 (see Table 5.8)				
OPEX	4	4	4	4	% CAPEX/year
Lifetime	30	30	30	30	years

The production of sustainable fuels requires additional feedstock. For example, ammonia requires N$_2$, methanol and SAF requires CO$_2$. Units for producing N$_2$ and CO$_2$ are considered to be within the sustainable fuels hub and the costs are presented in Tables 5.9 and 5.9. The CO$_2$ production unit costs are based on direct air capture (DAC) technology. The demand for each feedstock is shown in Table 5.7 above. Regarding HVO, the production of biodiesel from this type of approach requires as aforementioned, residual vegetable oils or animal fats, the cost of this type of feedstock was estimated by LNEG in 50 €/t.

Table 5.8: CAPEX considered for hydrogen liquefaction and conversion into other sustainable fuels in M€ [16, 17].

Scenario	LH2	AMM	MET	HVO	SAF
S2LH2100	462	-	-	-	-
S3AMM100	-	291	-	-	-
S4MET100	-	-	64	-	-
S5HVO100	-	-	-	1718	-
S6SAF100	-	-	-	-	90
S7ALLP20	92	58	13	343	34

Table 5.9: N_2 costs [16, 17].

Parameter	Value	Unit
Production rate	Based on scenarios	
Specific energy consumption	0.56	kWhel/kgN_2
Specific investments costs	129	€/t/year
Fixed operation costs	2	% CAPEX/year
Lifetime	30	years

Table 5.10: DAC CO_2 costs [16, 17].

Parameter	Methanol	Liquid Fuels (Fischer-Tropsch)	Unit
Electricity demand (w/o heat integration & heat pumps)	0.5	0.5	kWhel/kgCO_2
Thermal demand (w/o heat integration & heat pumps)	1.81	1.81	kWhth/kgCO_2
Thermal demand (after heat integration & w/heat pumps)	1.74	0	kWhth/kgCO_2
Heat pump: coefficient of performance	2.51	2.51	-
Total electricity demand of integrated DAC	1.19	0.5	kWhel/kgCO_2
Production rate	Based on scenarios		t/d
Specific investments costs	500		€/t/year
Fixed operation costs	4		% CAPEX/year
Lifetime	25		Year

5.2.4 Products storage and distribution

Products typical storage conditions and costs are shown in Table 5.11. The boil-off rate is only applicable to the liquefied hydrogen, and it represents the daily rate of evaporation when stored under the stated conditions. It is evident that because of these conditions, liquid hydrogen storage is the most expensive of all products shown.

The products were considered to be distributed through maritime transport. For this, information about different types of vessels, their capacities, conditions of operation, and costs was considered, based on previous studies [16, 17, 23–26] (see Table 5.12). For this study, it is assumed that the vessels are dedicated to the transport of the products from the sustainable fuels hub, and then the total costs are part of the project. Only one vessel will serve one kind of product, depending on the scenario, and the final costs are expressed as a levelised cost of maritime transport. This approach is applied to scenarios S2 to S7. For scenario S1GH2100, the distribution is assumed to be through the European Hydrogen Backbone (pipeline network for hydrogen). The costs associated with the distribution are presented in Table 5.13. The total pipeline distance from Leixões to Germany was estimated to be about 3000 km. For maritime transport, the distance considered was between the Port of Leixões in Portugal and the Port of Bremerhaven in Germany, which is approximately 2500 km.

Table 5.11: Storage characteristics and costs for products [16, 17].

Parameter	**LH2**	**NH3**	**MeOH**	**FT**	**Unit**
Storage volume	Dependent on rated production capacity (five days of storage)				
Product storage pressure	atm.	atm.	atm.	atm.	bar
Product storage temperature	-253	-33	ambient	ambient	°C
Storage density	71	682	794	763	kg/m^3
CAPEX	25,000	990	130	290	€/t
Fixed OPEX	2	2	2	2	% CAPEX/year
Boil-off rate	0.1	-	-	-	%/d
Lifetime	30	30	30	30	years

Table 5.12: Technical and economic parameters for transport vessels [16, 17, 23–26].

Parameter	**LH2**	**NH3**	**MeOH**	**FT**	**Unit**
Number of transport vessels	1	1	1	1	unit
Vessel type	LH_2 carrier (concept)	LPG carrier	Chemical tanker	MR 2 tanker	-
Transport volume	160,000	84,000	55,000	67,000	m^3
Transport capacity	11,360	57,288	43,676	49,593	t
Ship speed	16	15	15	15	knots
Boil-off rate	0.2	-	-	-	%/day
Rated engine power	25	13.3	7.8	7.8	MW
CAPEX	440	92	50	40	million EUR
Fixed OPEX		4			% CAPEX/year
Lifetime		25			years

Table 5.13: Hydrogen transport costs via pipeline network in Europe [16, 17].

Parameter	**Onshore**	**Offshore**	**Unit**
Specific hydrogen transportation costs	0.15	0.22	€/kg/1000 km

5.3 Comparison of alternatives

The results of the assessment of scenarios S1 to S6, which considered one main commodity to be commercialised at a time, are summarised in Table 5.14. The results shown in this table do not consider the distribution costs. The production capacity refers to each product, and the levelised cost of P2X is presented in € per tonne of product (commodity) and in € per MWh to facilitate comparisons. In addition, the total investment without considering the cost of the wind farm is also shown. Results show that green hydrogen, whether in gas or liquid form, remains a high-cost commodity compared to hydrogen obtained from other sources. However, its transformation into sustainable fuels can be competitive.

The results also showed that HVO might be a good option. The low cost of HVO is competitive with that of fossil fuels, primarily because of the reduced amount of hydrogen required to produce each tonne of HVO and the low cost of the residual oil used in the process. For each tonne of HVO produced, about 100 kg of hydrogen and 1200 kg of residual oils and animal fats are used. Taking into account the LCOX in €/MWh, the levelised cost of the obtained HVO was 86 €/MWh, while the average price of diesel in continental Portugal during the year 2024 was about 158 €/MWh [113]. In the European Union, the average cost in 2024 was approximately 172 €/MWh [113]. In these terms, it seems that the production of biodiesel from offshore wind electricity is a potential business case. Among the scenarios evaluated, HVO ranks as the number one commodity among the options evaluated.

Regarding ammonia, the current market price in February 2025 of green ammonia was between 924 to 1030 USD/t (about 887 to 989 €/t), depending on the origin of the commodity [114]. The results in this report show a levelised cost of ammonia of 1598 €/t, which is about 30% higher than the price referred to above. Gray ammonia is substantially cheaper (about 561 €/t for the same period). On the other hand, methanol has a market price of about 600 €/t for Europe [115]. The results of methanol production through a P2X strategy from offshore wind has values of 2200 €/t, which is almost fourfold higher. With respect to jet fuel, the current price for Europe is about 690 €/t, being the levelised cost of SAF obtained from scenario S6SAF100 5612 €/t. The significantly high costs of methanol and SAF are due to the higher hydrogen feedstock required for their production compared to HVO, for example, and the costs associated with the CO_2 capture required for the syntheses. Similar results were obtained for scenario S7ALLP20, which are presented in Table 5.15. There are no cost differences because economies of scale were not considered in the computations.

There is an opportunity to produce sustainable fuels using green hydrogen in Portugal, contributing to Europe's energy independence goals.

Table 5.14: Results for scenarios S1 to S6 considered in this study.

Parameter	**GH2**	**LH2**	**AMM**	**MET**	**HVO**	**SAF**
Scenario	S1GH2100	S2LH2100	S3AMM100	S4MET100	S5HVO100	S6SAF100
Offshore Wind LCOE [€/MWh]	135.4					
Production Capacity [t/d]	180	180	1000	920	2250	360
LCOX[1] [€/MWh]	259	315	308	361	86	472
LCOX[2] [€/t]	8642	10515	1598	2273	1044	5612
Total Investment[3] [M€]	458	942	793	763	2180	829

[1] It does not include the maritime transport of products or gaseous hydrogen transport through pipelines. The value is computed as the the number of tonnes of product per year times the LHV energy content of the product.

[2] The unit is euros per tonne of product. It does not include the maritime transport of products or gaseous hydrogen transport through pipelines

[3] Offshore wind farm investment costs are not included

Figure 5.2 presents the relative share between CAPEX, OPEX, electricity, and water that contribute to LCOX for the five main commodities considered in the analysis. The reader should

Table 5.15: Results for scenarios S7 considered in this study.

Parameter	**GH2**	**LH2**	**AMM**	**MET**	**HVO**	**SAF**
Scenario	S7ALLP20					
Offshore Wind LCOE [€/MWh]	135.4					
Production Capacity [t/d]	180	36	200	185	450	72
LCOX[1] [€/MWh]	259	315	308	361	86	472
LCOX[2] [€/t]	8642	10515	1598	2273	1044	5612
Total Investment[3] [M€]	458	555	525	559	802	580

[1] It does not include the maritime transport of products or gaseous hydrogen transport through pipelines. The value is computed as the number of tonnes of product per year times the LHV energy content of the product.

[2] The unit is euros per tonne of product. It does not include the maritime transport of products or gaseous hydrogen transport through pipelines

[3] Offshore wind farm investment costs are not included

be aware that the term OPEX here refers to fixed annual OPEX, i.e., electricity and water are not included. These are accounted separately. From Figure 5.2, it is evident that electricity is the largest contributor, weighing more than 80% of LCOX, with the exception of HVO with approximately 67%, which is less energy-intensive among the options. Consequently, it turns out that sustainable fuel production and green hydrogen are mainly OPEX-dependent businesses, and thus any public measure to support these innovative business models is important during their lifetime.

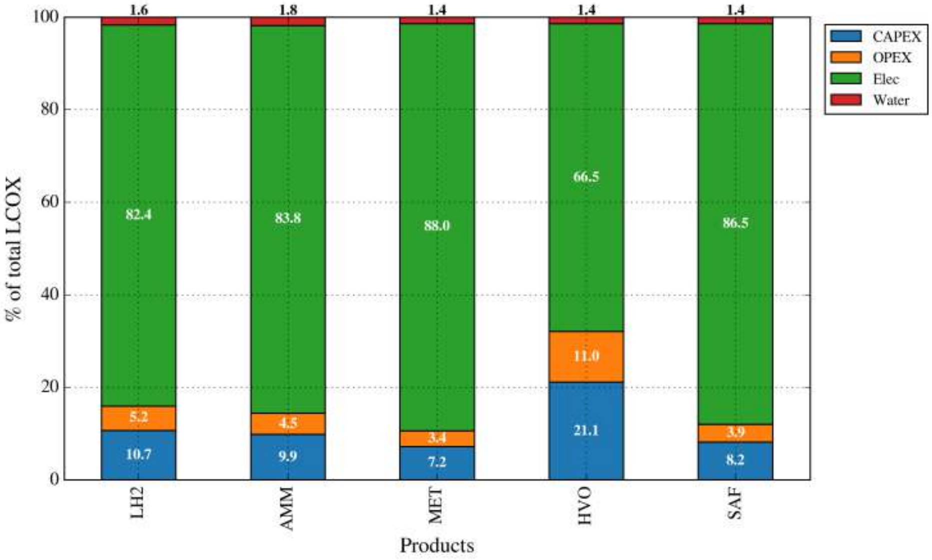


Figure 5.2: LCOX percentage distribution for "X" products: Liquid hydrogen (LH_2), ammonia (AMM), methanol (MET), biodiesel from hydrotreated vegetable oil (HVO), sustainable aviation fuel (SAF). Scenarios S2 to S6. Source: LNEG.

Figure 5.3 presents the percentage contribution to LCOX of different processes and feedstocks within the value chain of ammonia, methanol, HVO, and SAF. It is evident that the feedstock represents the most important contributor to the LCOX, with green hydrogen being the largest. CO_2 direct capture from air is also an important component in the cost structure. For HVO, production represents more than a quarter of the LCOX. In contrast, storage costs represent a weak contribution to the LCOX. It is important to note that the storage systems associated with all production units were sized to store five days of production. More storage capacity will evidently increase this storage contribution to the LCOX. A complete optimisation of the Green Hydrogen and Sustainable Fuels Hub shall be carried out for a more robust analysis. However, as exploratory scenarios for P2X and offshore wind in Portugal, the results presented here are deemed acceptable to have a better idea of potential business cases.

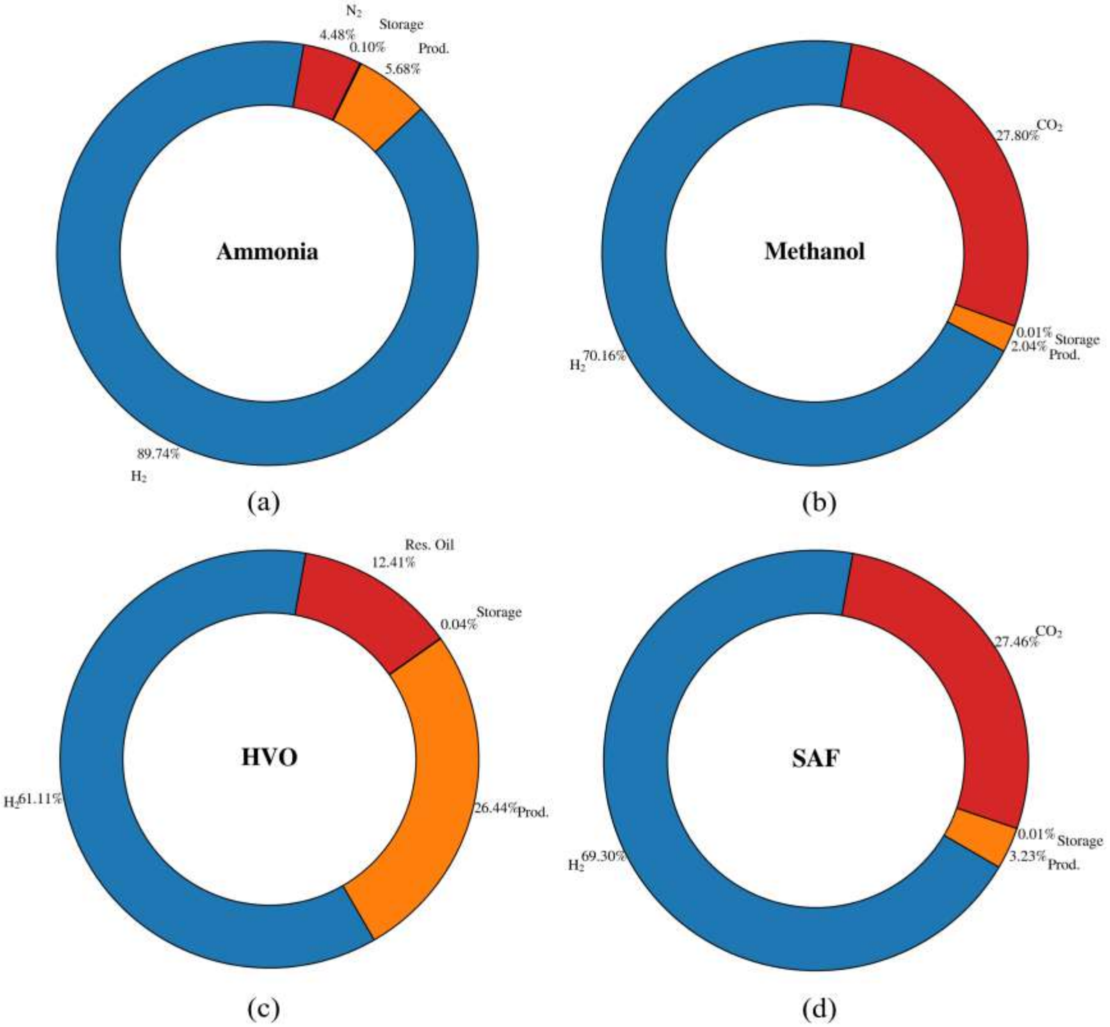


Figure 5.3: Relative contribution to the LCOX of different processes and feedstock within the value chain of (a) ammonia, (b) methanol, (c) HVO, and (d) SAF.

5.3.1 Distribution costs in the total LCOH and LCOX

The LCOH and LCOX considering the distribution costs for hydrogen and sustainable fuels are presented in Tables 5.16 and 5.17 for all seven scenarios. The increases in LCOH associated with the distribution of gas and liquid hydrogen are 6.2% and 7.9%, corresponding to scenarios S1 and S2, respectively. The maritime transport of ammonia, methanol, HVO, and SAF represents an increase in LCOX of less than 1% (scenarios S3 to S6). Regarding scenario S7 (S7ALLP20), it shows the highest differences, as it considers the production of all types of products and the distribution of liquid hydrogen, ammonia, methanol, HVO, and SAF, and the quantities produced are small and would reflect in higher maritime transport costs considering investment in vessels. The increase in LCOH associated with the distribution of the amount of hydrogen produced in the latter scenario would be about 38%, while for the LCOX of ammonia, methanol, and SAF, it would be approximately 5.5%, 3.4%, and 5.3%, respectively. For HVO, the increase is negligible. Strategies should be in place to minimise the cost of distribution of the commodities. In this study, optimisation is not considered. The results show that the distribution of products might represent a significant cost that must be minimised.

Table 5.16: Results for scenarios S1 to S6 considering distribution of products.

Parameter	**GH2**	**LH2**	**AMM**	**MET**	**HVO**	**SAF**
Scenario	S1GH2100	S2LH2100	S3AMM100	S4MET100	S5HVO100	S6SAF100
Distribution mode	Pipeline	Maritime Transport				
LCOX[1] incl. distribution [€/MWh]	275	340	311	363	86	474
LCOX[2] incl. distribution [€/t]	9151	11342	1617	2289	1050	5645

[1] Computed as the number of tonnes of product per year times the LHV energy content of the product
[2] The unit is euros per tonne of product

Table 5.17: Results for scenarios S7 considering distribution of products.

Parameter	**LH2**	**AMM**	**MET**	**HVO**	**SAF**
Scenario	S7ALLP20				
Distribution mode	Maritime Transport				
LCOX[1] incl. distribution [€/MWh]	436	325	364	87	497
LCOX[2] incl. distribution [€/t]	14533	1692	2299	1071	5923

[1] Computed as the number of tonnes of product per year times the LHV energy content of the product
[2] The unit is euros per tonne of product

5.4 Sensitivity analysis

A sensitivity analysis was performed considering the largest contributors to LCOH and LCOX. The parameters varied parametrically are the following:

(i) The CAPEX of the hydrogen production unit;

(ii) the cost of electricity for the hydrogen and sustainable fuels hub, which is expressed as the offshore wind LCOE;

(iii) the load factor of the hydrogen production unit, which expresses the ratio of the equivalent number of hours working at the rated capacity over the hours in a year; and

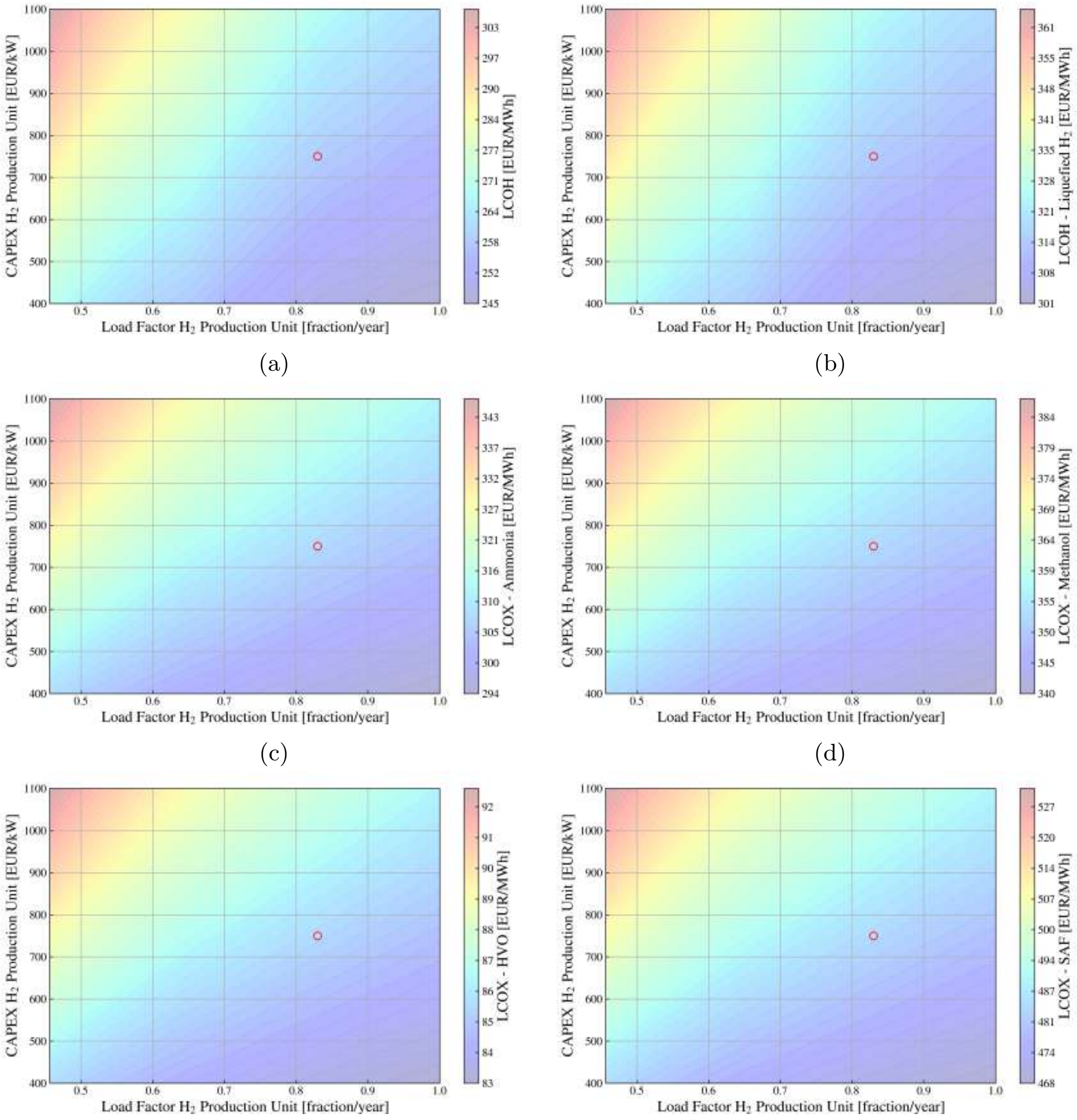
(iv) the weighted average cost of capital of the project, which affects the project.

The results are presented in Figures 5.4, 5.5, and 5.6. The figures represent colour maps with the variation of two variables simultaneously and their effect on the LCOH or LCOX expressed in €/MWh. The main takeaways are the following.

- HVO production continues to be an attractive option for an offshore wind P2X approach. The highest LCOX for HVO was found to be less than 110 €/MWh, which occur at a

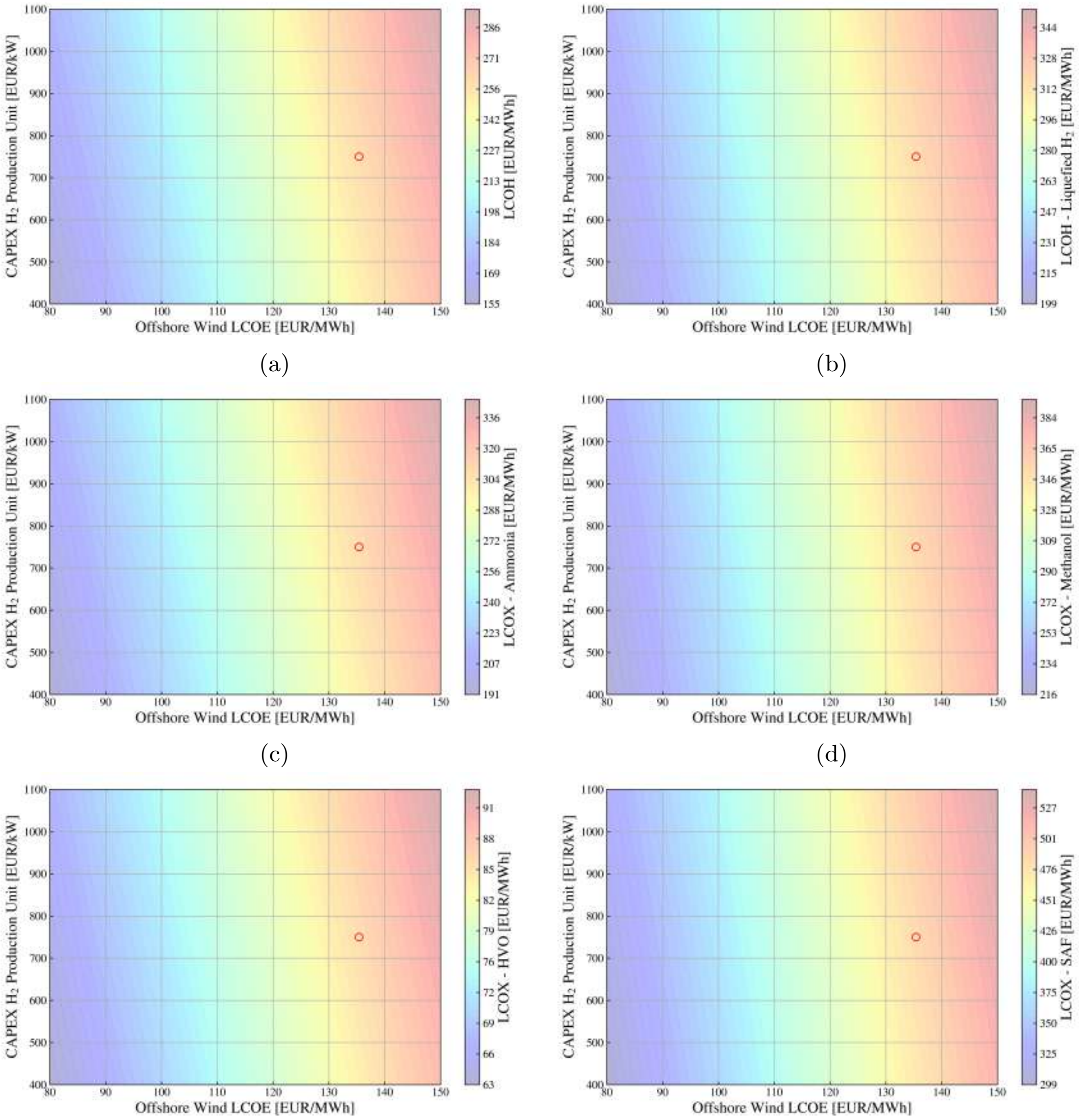
WACC of 12% and unit CAPEX for the green hydrogen production unit of 1100 €/kW of electrolysers capacity (see Figure 5.6(e)).

- Ammonia could become competitive with other green ammonia supplies from other places in the world for low LCOE (see Figure 5.5(c)). However, it presents higher costs than grey ammonia.
- Methanol, SAF, and liquefied hydrogen resulted in higher LCOX and LCOH within the scenarios analysed. More innovation efforts are recommended to enhance efficiency in conversion, storage, and distribution processes, thereby reducing costs.
- Hydrogen production and storage in gas form can decrease costs to less than 5 €/kg when the LCOE (i.e., cost of electricity) is low (i.e. for LCOE below 80 €/MWh), which remains a challenge for floating offshore wind in the next decade (see Figure 5.5(a)). Instead, with onshore renewable electricity, it may be a real option to produce green hydrogen at lower costs.



(a) (b) (c) (d) (e) (f)

Figure 5.4: Sensitivity analysis results of the LCOH and LCOX considering the variation of the CAPEX and the load factor of the hydrogen production unit. (a) GH_2, (b) LH_2, (c) Ammonia, (d) Methanol, (e) HVO, and (f) SAF. Red circles represent the base cases.



(a)

(b)

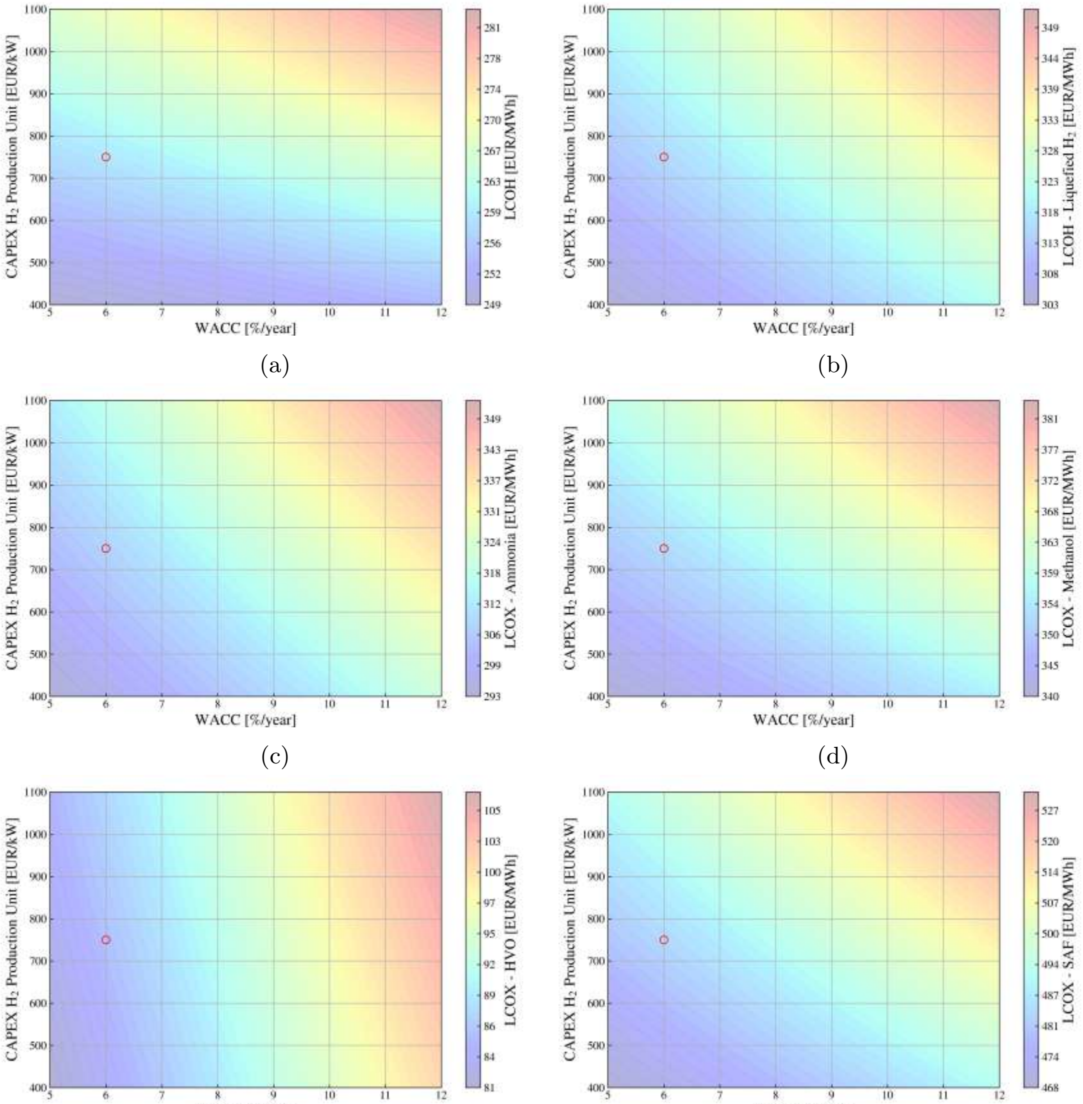
(c)

(d)

(e)

(f)

Figure 5.5: Sensitivity analysis results of the LCOH and LCOX considering the variation of the CAPEX of the hydrogen production unit and the offshore wind LCOE. (a) GH_2, (b) LH_2, (c) Ammonia, (d) Methanol, (e) HVO, and (f) SAF. Red circles represent the base cases.



(a) (b) (c) (d) (e) (f)

Figure 5.6: Sensitivity analysis results of the LCOH and LCOX considering the variation of the CAPEX of the hydrogen production unit and the WACC of the hydrogen and sustainable fuels hub. (a) GH_2, (b) LH_2, (c) Ammonia, (d) Methanol, (e) HVO, and (f) SAF. Red circles represent the base cases.

6 Conclusions and recommendations

This section summarises the findings for the uptake of offshore wind and Power-to-X (P2X) options in Portugal. It also aims to highlight recommendations that may accelerate technological developments, innovation, and feasible business models.

This report compiled information on the state-of-the-art strategies underway for offshore wind and green hydrogen in Portugal, introduced the P2X concept, discussed potential offshore wind P2X business models, described the main processes and technologies involved in P2X efforts, mapped potential consumers of green hydrogen and the supply chain of hydrogen and sustainable fuels, and investigated the techno-economics of P2X options considering a number of scenarios with the objective of identifying potential competitive pathways for Portugal. The following are the key general highlights.

- **Offshore floating wind** comprises a set of technologies still under development with small farms up to 100 MW, not yet in mainstream commercialisation, and the levelised cost of electricity from this source is higher than fixed-bottom deployments. In Portugal, the main areas identified for future public auctions are for offshore floating wind. The electricity costs would be transferred to any offshore wind P2X business model.
- The **load factor of green hydrogen production units**, i.e. the number of total operational hours in a year at equivalent rated power, is fundamental for the viability of any P2X strategy considering hydrogen as a commodity or feedstock for synfuels. The supply of electricity from complementary renewable sources onshore should also be considered to keep the load factor as close to 100% as possible. This additional electricity may come from the national electricity network or from a dedicated infrastructure through PPAs.
- The **weighted average cost of capital (WACC)**, or the total project discount rate, is critical for enabling potential businesses. This is related to the risk perception of investors and financing organisations; lower risk perception will enable a reduction in WACC and increase the willingness to invest and finance. In this sense, all stakeholders, including policymakers, must be concerned about derisking the sector.
- **Capital costs** are decisive for any P2X project development, and in this sense, sourcing of goods and services should allow CAPEX reduction. Technologies with the highest impact on CAPEX are those related to green hydrogen production (water electrolysis), CO_2 capture, and HVO and ammonia production. Targeting technology developments and industrialisation on these will aid in CAPEX reduction. Local supply chains on the right scales might be a competitive advantage for Portugal.
- An emerging **Portuguese supply chain** was identified with about 130 companies with activities that may act in the value chain of hydrogen and sustainable fuels, and also about 140 companies related to offshore wind and other renewables, a sector in which Portugal has historical competitive advantages. The country hosted pioneering projects in floating wind and wave energy motivated by its large offshore renewable energy resources.

- P2X projects involving green hydrogen and sustainable fuels are **OPEX** cost-intensive. This means that the derisking actions should pass by creating a favourable commercial environment for businesses in all the value and supply chains related to the P2X business models. More than 75% of the LCOH or LCOX comes from total operational expenditures, i.e. electricity, fixed O&M costs, and water (named in importance order).

This study considered the techno-economic analysis of the following offshore wind P2X options: i) the Production and storage of hydrogen in gas form, ii) its liquefaction and storage in liquid form, iii) the production and storage of ammonia, iv) the production and storage of methanol, v) production and storage of biodiesel from hydrotreated vegetable oils (HVO), and vi) production and storage of sustainable aviation fuels (SAF). Also, the distribution of the different products (commodities) was considered. The gaseous hydrogen distribution was considered to be via the European Hydrogen Backbone from Portugal to Germany. The distribution of liquid hydrogen and other sustainable fuels was considered to be via maritime transport. The levelised cost of hydrogen (LCOH) and X (LCOX) were the main indicators for comparing the different offshore wind P2X scenarios in this study. The main findings are the following.

- **HVO production stood out among the offshore wind P2X options studied.** The LCOX for HVO was found to be between 63 and 110 €/MWh, an interval which is lower than the average price of diesel in continental Portugal and Europe during the year 2024, about 158 and 172 €/MWh, respectively.
- **Ammonia could become competitive with other green ammonia supplies** from other places in the world due to its low LCOE, which is **most probably achievable when the electricity source is from renewables onshore**. However, it presents higher costs than grey ammonia.
- **Methanol, SAF, and liquefied hydrogen resulted in higher LCOX and LCOH within the scenarios analysed**. More innovation efforts are recommended to enhance efficiency in conversion, storage, and distribution processes, thereby reducing costs.
- **Hydrogen production and storage in gas form can decrease costs to less than 5 €/kg** when the LCOE (i.e., low cost of electricity) is low (i.e. for LCOE below 80 €/MWh), which remains a challenge for floating offshore wind in the next decade. Instead, **with onshore renewable electricity**, it may be a real option to produce green hydrogen at lower costs.

The following recommendations are drawn up for policymakers:

- **Efforts should be directed towards the development up to market readiness level of technologies related to hydrogen production and the production, storage, and distribution of sustainable fuels**. Support for technology R&D and innovation, and industrialisation of national production is of utmost importance to reduce CAPEX. Emphasis should be placed in promoting the development and strengthening of Portuguese industrial value chains in these domains.
- However, actions should not only be directed to support CAPEX reductions; in fact, the most important share in the costs of a P2X project is associated with the operating and maintenance expenses (OPEX). **Substantial efforts should be directed to enable the**

reduction of costs during the operating lifetime of the hydrogen and sustainable fuels businesses. **Fiscal incentives that cover the entire lifetime of the projects could be considered, especially for pilot, demonstration, and the first large projects.**

- But also, **incentives might also be key to aid CAPEX reduction**. This could be achieved by **creating favourable conditions for the entire supply chain of goods and services associated with P2X projects**, especially for pilot, demonstration, and the first large projects.
- **A clear regulatory framework to enable agile licensing processes is fundamental** to reducing bottlenecks and derisking offshore wind and P2X projects.

Portugal's strategic approach to offshore wind and P2X technologies positions the country as a frontrunner in the decarbonisation of the economy. By leveraging its extensive coastal resources and fostering a supportive policy environment, Portugal is set to transform its energy landscape and drive sustainable economic growth. This report provides a comprehensive analysis to guide stakeholders in realising the full potential of these initiatives.

Bibliography

[1] Portuguese Government, Resolução do conselho de ministros n.o 19/2025 (2025).
URL `https://diariodarepublica.pt/dr/detalhe/resolucao-conselho-ministros/19-2025-906519104`

[2] Dolphyn Hydrogen, Where we are: Commercial demonstrator (2023).
URL `https://www.dolphynhydrogen.com/where-we-are#commercial-demonstrator`

[3] The Maritime Executive, Korea adds hydrogen plant as it approves giant floating wind farm plan (2021).
URL `https://maritime-executive.com/article/korea-adds-hydrogen-plant-as-it-approves-giant-floating-wind-farm-plan`

[4] Oyster Consortium, Oyster project (2021).
URL `https://oysterh2.eu/`

[5] J. Watson, Y. Ojo, I. Lestas, C. Spanias, Stability of power networks with grid-forming converters, in: 2019 IEEE Milan PowerTech, 2019, pp. 1–6. `doi:10.1109/PTC.2019.8810506`.

[6] M. W. Shahzad, M. Burhan, L. Ang, K. C. Ng, Energy-water-environment nexus underpinning future desalination sustainability, Desalination 413 (2017) 52–64. `doi:10.1016/j.desal.2017.03.009`.

[7] Direção-Geral de Energia e Geologia, Balanços energéticos nacionais (2025).
URL `https://www.dgeg.gov.pt/pt/estatistica/energia/balancos-energeticos/balancos-energeticos-nacionais/`

[8] LNEG, A Portuguese Atlas of Sustainable Green H2 (2025).
URL `https://geoportal.lneg.pt/mapa/?mapa=AtlasH2Verde`

[9] en:former, H2MED pipelines to supply Europe with hydrogen (2023).
URL `https://www.en-former.com/en/h2med-pipelines-to-supply-europe-with-hydrogen/`

[10] MadoquaPower2X, MadoquaPower2X (2025).
URL `https://www.power2x.com/madoqua-power2x/`

[11] Danish Energy Agency, PtX and CCUS Technology Export Potential (2023).
URL `https://ens.dk/sites/ens.dk/files/ptx/ptx_and_ccus_technology_export_potential.pdf?utm_referrer=https%3A%2F%2Framboll.com%2F`

[12] FutureBridge, Grid-forming inverters: Shaping the future of power distribution (2023).
URL `https://www.futurebridge.com/industry/perspectives-energy/grid-forming-inverters-shaping-the-future-of-power-distribution`

[13] H. Nassrullaha, S. F. Anisa, R. Hashaikeha, N. Hilala, Energy for desalination: A state-of-the-art review, Desalination (2020). `doi:10.1016/j.desal.2020.114569`.

[14] I. C. Karagiannis, P. G. Soldatos, Water desalination cost literature: Review and assessment, Desalination 223 (1-3) (2008) 448–456. `doi:10.1016/j.desal.2007.02.071`.

[15] S. G. Simões, J. Catarino, A. Picado, T. F. Lopes, S. di Berardino, F. Amorim, F. Gírio, C. M. Rangel, T. P. de Leão, Water availability and water usage solutions for electrolysis in hydrogen production, Journal of Cleaner Production 315 (2021) 128124. `doi:10.1016/j.jclepro.2021.128124`.

[16] C. Hank, M. Holst, C. Thelen, C. Kost, S. Längle, A. Schaadt, T. Smolinka, Site-specific, Comparative Analysis for Suitable Power-to-X Pathways and Products in Developing and Emerging Countries (2023).
URL `https://www.ise.fraunhofer.de/en/publications/studies/power-to-x-country-analyses.html`

[17] Fraunhofer ISE, Power-to-X Colombia: Green Hydrogen and Derivatives Production, study carried out within the Colombian-German Dialog on Re-Industrialization via Renewable Hydrogen (2024).
URL `https://www.ise.fraunhofer.de/en/publications/studies/power-to-x-colombia.html`

[18] M. Holst, S. Aschbrenner, T. Smolinka, C. Voglstätter, G. Grimm, Cost forecast for low temperature electrolysis - Technology driven bottom-up prognosis for PEM and alkaline water electrolysis systems (2022). `doi:10.24406/publica-1318`.

[19] Clean Hydrogen Joint Undertaking, Strategic Research and Innovation Agenda 2021 – 2027: Annex to GB decision no. CleanHydrogen-GB 2022-02 (2022).
URL `https://www.clean-hydrogen.europa.eu/about-us/key-documents/strategic-research-and-innovation-agenda_en`

[20] International Energy Agency, The future of hydrogen - assumption annex: Seizing today's opportunities (2019).
URL `https://www.iea.org/reports/the-future-of-hydrogen`

[21] U. Caldera, D. Bogdanov, C. Breyer, Local cost of seawater RO desalination based on solar PV and wind energy: A global estimate, Desalination 385 (2016) 207–216. `doi:10.1016/j.desal.2016.02.004`.

[22] DesalData, Desalination cost estimator (2022).
URL `https://www.desaldata.com/`

[23] M. Vos, J. Douma, A. von den Noort, Study on the import of liquid renewable energy: Technology cost assessment, Tech. rep., DNV GL (2020).
URL `https://www.gie.eu/wp-content/uploads/filr/2598/DNV-GL_Study-GLE-Technologies-and-costs-analysis-on-imports-of-liquid-renewable-energy.pdf`

[24] C. Stemmler, J. Thesen, M. Bartusevičiūtė, HySupply: A meta-analysis towards a german-australian supply-chain for renewable hydrogen: Working paper (2021).
URL `https://www.acatech.de/wp-content/uploads/2020/11/HySupply_WorkingPaper_Meta-Analysis.pdf`

[25] Y. Seo, S. Han, Economic evaluation of an ammonia-fueled ammonia carrier depending on methods of ammonia fuel storage, Energies 14 (2021) 8326. `doi:10.3390/en14248326`.

[26] MAN Energy Solutions, Propulsion trends in tankers (2021).
URL `https://www.man-es.com/docs/default-source/marine/tools/propulsion-trends-in-tankers_5510-0031-03ppr.pdf?sfvrsn=399654ef_4`

[27] European Commission, European Climate Law (2023).
URL `https://climate.ec.europa.eu/eu-action/european-green-deal/european-climate-l`

aw_en#:~:text=The%20Climate%20Law%20includes%3A,of%20emission%20reductions%20and%20removals

[28] European Commission, European Green Deal (2023).
URL https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

[29] European Commission, Fit for 55: Delivering the European Green Deal (2023).
URL https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal/fit-55-delivering-proposals_en#:~:text=Under%20the%20European%20Climate%20Law,fit%20to%20meet%20this%20target

[30] European Commission, Press release (2023).
URL https://ec.europa.eu/commission/presscorner/detail/en/IP_23_2061

[31] European Commission, An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future (2020).
URL https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:741:FIN&qid=1605792629666

[32] European Commission, A hydrogen strategy for a climate-neutral Europe (2020).
URL https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301

[33] European Commission, Offshore Renewable Energy (2023).
URL https://energy.ec.europa.eu/topics/renewable-energy/offshore-renewable-energy_en

[34] Portuguese Government, Resolution of the Council of Ministers no 170/2019. Roadmap for carbon neutrality 2050 (RNC2050). Long-term strategy for carbon neutrality of the Portuguese economy by 2050 (2019).

[35] Council of Ministers, Resolution 53/2020: Portuguese PNEC - National Energy and Climate Plan (in Portuguese) (2020).

[36] Portuguese Government, Lei n.o 98/2021 de de 31 de dezembro de 2021 que estabelece a lei de bases do clima (2021).
URL https://files.dre.pt/1s/2021/12/25300/0000500032.pdf

[37] Portuguese Government, Decreto-lei n.o 84/2022 (2022).
URL https://diariodarepublica.pt/dr/detalhe/decreto-lei/84-2022-204502328

[38] Portuguese Parliament, Resolução da assembleia da república n.o 127/2025 (2025).
URL https://diariodarepublica.pt/dr/detalhe/resolucao-assembleia-republica/127-2025-914597185

[39] Portuguese Government, Draft Revision of the Portuguese NECP. PORTUGAL - PLANO NACIONAL ENERGIA E CLIMA 2021-2030 (PNEC 2030). Atualização/Revisão (de acordo com o definido no artigo 14o do Regulamento (UE) 2018/1999, de 11 de dezembro) (2023).

[40] EUROSTAT, SHARES - SHort Assessment of Renewable Energy Sources by EUROSTAT, SHARES up to 2020 and 2021 - summary results (2021).
URL https://thg-projektionen2025-daten-modell-dokumentation-788cd5.usercontent.opencode.de/Datensatz/enusem_res_shares/#dieser-datensatz-im-modellierungsprozess

[41] Portuguese Government, Draft 2nd Revision of the Portuguese NECP. PORTUGAL - PLANO NACIONAL ENERGIA E CLIMA 2021-2030 (PNEC 2030). Atualização/Revisão (de acordo com o definido no artigo 14o do Regulamento (UE) 2018/1999, de 11 de dezembro) (2024).
URL `https://apambiente.pt/sites/default/files/_Clima/20241118_pnec2030_para_aprov_ar.pdf`

[42] S. G. Simões, T. Simões, J. Barbosa, C. Rodrigues, P. Azevedo, J. P. Cardoso, J. Facão, P. A. Costa, P. Justino, F. Gírio, A. Reis, P. C. Passarinho, L. Duarte, P. Moura, M. Abreu, A. Estanqueiro, A. Couto, P. Oliveira, L. Quental, P. Patinha, J. Catarino, A. Picado, Estimate of Technical Renewable Energy Potentials for Portugal [Estimativa de Potenciais Técnicos De Energia Renovável em Portugal] (in Portuguese) (2023).
URL `https://repositorio.lneg.pt/entities/publication/48c5065c-dbad-42b4-a568-0e5437c56e3c`

[43] DGRM, DGEG, LNEG, ERSE, REN, APREN, APP, Relatório do Grupo de Trabalho para o planeamento e operacionalização de centros eletroprodutores baseados em fontes de energias renováveis de origem ou localização oceânica (Despacho n.o 11404/2022, de 23 de setembro) - Versão final (2023).

[44] Portuguese Government, Decreto-lei n.o 185/2022 (2022).
URL `https://files.dre.pt/2s/2022/09/185000000/0006200065.pdf`

[45] Portuguese Government, Portuguese National Hydrogen Strategy ENH2 - Portuguese RCM 63/2020, August 14th (2020).

[46] Ramboll, Power-to-X Explained (2023).
URL `https://www.ramboll.com/net-zero-explorers/power-to-x-explained`

[47] WindFloat Atlantic, WindFloat Atlantic 2023 (2023).
URL `https://www.windfloat-atlantic.com/`

[48] LNEG, Offshore Plan Project (2018).
URL `https://offshoreplan.lneg.pt/`

[49] D. Santos, P. Costa, P. Justino, J. Silva, A. Couto, T. Simões, et al., Planning the Use of Offshore Renewable Energy in Portugal, D2.1 - Methodologies to assess the renewable offshore resources. Project Offshore Plan (2017).
URL `https://www.lneg.pt/en/project/offshoreplan-2/`

[50] G. Garcia, T. Simões, D. Santos, H. Rybchynska, A. Estanqueiro, OffshorePlan - Planeamento do Aproveitamento das Energias Renováveis Offshore em Portugal. Deliverable 3.1 Definição e implementação das metodologias de identificação de áreas de interesse para a instalação de sistemas de produção renovável offshore (2018).
URL `https://www.lneg.pt/en/project/offshoreplan-2/`

[51] EPRS - European Parliamentary Research Service, Briefing Offshore Wind Energy in Europe (2020).
URL `https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/659313/EPRS_BRI(2020)659313_EN.pdf`

[52] T. Stehly, P. Duffy, D. M. Hernando, 2022 Cost of Wind Energy Review, Tech. rep., National Renewable Energy Laboratory (2023).
URL `https://www.nrel.gov/docs/fy24osti/88335.pdf`

[53] A. Martinez, G. Iglesias, Mapping of the levelised cost of energy for floating offshore wind in the European Atlantic, Renewable and Sustainable Energy Reviews 154 (2022) 111889. `doi:10.1016/j.rser.2021.111889`.

[54] DNV, Floating offshore wind: The next five years (2023).
URL `https://www.dnv.com/focus-areas/floating-offshore-wind/#:~:text=DNV%E2%80%99s%20ETO%202023%20estimates%20that%20by%202050%2C%20the,increases%2C%20standardization%20and%20the%20advantages%20of%20experiential%20learning`

[55] United Nations Framework Convention on Climate Change, The Paris Agreement (2015).
URL `https://unfccc.int/process-and-meetings/the-paris-agreement`

[56] International Energy Agency, Renewables 2021: Analysis and forecast to 2026 (2021).
URL `https://iea.blob.core.windows.net/assets/5ae32253-7409-4f9a-a91d-1493ffb9777a/Renewables2021-Analysisandforecastto2026.pdf`

[57] Ramboll, Offshore hydrogen at scale (2023).
URL `https://www.ramboll.com/net-zero-explorers/offshore-hydrogen-at-scale`

[58] U.S. Department of Energy, How wind energy can help clean hydrogen contribute to a zero-carbon future (2023).
URL `https://www.energy.gov/eere/articles/how-wind-energy-can-help-clean-hydrogen-contribute-zero-carbon-future`

[59] ITM Power, Industrial scale renewable hydrogen project advances to next phase (2023).
URL `https://itm-power.com/news/industrial-scale-renewable-hydrogen-project-advances-to-next-phase`

[60] S. Alshahrani, K. Khan, M. Abido, M. Khalid, Grid-forming converter and stability aspects of renewable-based low-inertia power networks: Modern trends and challenges, Arabian Journal for Science and Engineering 49 (5) (2024) 6187–6216. `doi:10.1007/s13369-023-08399-z`.

[61] S. Rogalla, C. Schöll, P. Ernst, R. Singer, H. Lens, T. Schaupp, J. Ungerland, Grid-forming converters in interconnected power systems: Requirements, testing aspects, and system impact, IET Renewable Power Generation (2024) 1–14`doi:10.1049/rpg2.12967`.

[62] B. Kroposki, A. Hoke, Grid-forming electric inverters will unleash renewable energy - Getting the Grid to Net Zero, IEEE Spectrum (April 2024).
URL `https://spectrum.ieee.org/electric-inverter`

[63] B. Kroposki, Introduction to grid forming inverters: A key to transforming our power grid [slides], Tech. rep., OSTI.GOV (2024).
URL `https://www.osti.gov/biblio/2377167`

[64] Y. Zhou, R. Zhang, D. Kathriarachchi, J. Dennis, S. Goyal, Grid forming inverter and its applications to support system strength–a case study, IET Generation, Transmission and Distribution 17 (2) (2023) 391–398. `doi:10.1049/gtd2.12566`.

[65] H. Pishbahar, F. Blaabjerg, H. Saboori, Emerging grid-forming power converters for renewable energy and storage resources integration – A review, Sustainable Energy Technologies and Assessments 60 (2023) 103538. `doi:10.1016/j.seta.2023.103538`.

[66] S. W. Ali, M. Sadiq, Y. Terriche, S. A. R. Naqvi, L. Q. N. Hoang, M. U. Mutarraf, M. A. Hassan, G. Yang, C.-L. Su, J. M. Guerrero, Offshore wind farm-grid integration: A review on infrastructure, challenges, and grid solutions, IEEE Access 9 (2021) 102811–102827. `doi:10.1109/ACCESS.2021.3098705`.

[67] D. Wu, G.-S. Seo, L. Xu, C. Su, L. Kocewiak, Y. Sun, Z. Qin, Grid integration of offshore wind power: Standards, control, power quality and transmission, IEEE Open Journal of Power Electronics 5 (2024) 583–604. `doi:10.1109/OJPEL.2024.3390417`.

[68] M. W. Raza, M. Raza, Grid forming converters in offshore wind farms for grid integration through hybrid hvdc transmission system, International Journal of Renewable Energy Research 12 (3) (2022) 1552–1565. `doi:10.20508/ijrer.v12i3.13047.g8540`.

[69] B. Bahrani, M. H. Ravanji, B. Kroposki, D. Ramasubramanian, X. Guillaud, T. Prevost, N. A. Cutululis, Grid-forming inverter-based resource research landscape: Understanding the key assets for renewable-rich power systems, IEEE Power and Energy Magazine 22 (2) (2024) 18–29. `doi:10.1109/MPE.2023.3343338`.

[70] B. Shakerighadi, N. Johansson, R. Eriksson, P. Mitra, A. Bolzoni, A. Clark, H. P. Nee, An overview of stability challenges for power-electronic-dominated power systems: The grid-forming approach, IET Generation, Transmission and Distribution 17 (2) (2023) 284–306. `doi:10.1049/gtd2.12430`.

[71] M. Khan, W. Wu, L. Li, Grid-forming control for inverter-based resources in power systems: A review on its operation, system stability, and prospective, IET Renewable Power Generation 18 (6) (2024) 887–907. `doi:10.1049/rpg2.12991`.

[72] L. Huang, C. Wu, D. Zhou, L. Chen, D. Pagnani, F. Blaabjerg, Challenges and potential solutions of grid-forming converters applied to wind power generation system—an overview, Frontiers in Energy Research 11 (2023) 1–14. `doi:10.3389/fenrg.2023.1040781`.

[73] D. Pagnani, L. Kocewiak, J. Hjerrild, F. Blaabjerg, C. L. Bak, Control principles for island operation and black start by offshore wind farms integrating grid-forming converters, in: 24th European Conference on Power Electronics and Applications, EPE 2022 ECCE Europe, 2022.

[74] Pacific Northwest National Laboratory, New Grid-Forming Inverter Models Help Utilities Plan for a Renewable Future (2024).
URL `https://www.pnnl.gov/publications/new-grid-forming-inverter-models-help-utilities-plan-renewable-future`

[75] North American Electric Reliability Corporation (NERC), White paper: Grid forming functional specifications for bps-connected battery energy storage systems (September 2023).
URL `https://www.nerc.com/comm/RSTC_Reliability_Guidelines/White_Paper_GFM_Functional_Specification.pdf`

[76] ESIG, Grid-forming technology in energy systems integration (March 2022).
URL `https://www.esig.energy/reports-briefs`

[77] N. Mlilo, J. Brown, T. Ahfock, Impact of intermittent renewable energy generation penetration on the power system networks – A review, Technology and Economics of Smart Grids and Sustainable Energy 6 (1) (2021) 1–19. `doi:10.1007/s40866-021-00123-w`.

[78] ENTSO-E, European Network of Transmission System Operators for Electricity Vision on Market Design and System Operation towards 2030 (2019).
URL `https://vision2030.entsoe.eu/wp-content/uploads/2019/11/entsoe_fp_vision_2030_web.pdf`

[79] ENTSO-E, Network code for requirements for grid connection applicable to all generators (2016).
URL `https://www.entsoe.eu/network_codes/rfg/`

[80] D. Venkatramanan, R. Henriquez-Auba, M. R. K. Rachi, J. T. Bui, M. K. Singh, D. Ramasubramanian, A. Hoke, B. Kroposki, S. Dhople, Grid-forming inverter technology specifications: A review of research reports and roadmaps (November 2022). `doi:10.13140/RG.2.2.21509.22249`.

[81] FutureBridge, Push for renewables: Grid integration challenges and technologies (May 2022). URL `https://www.futurebridge.com/industry/perspectives-energy/push-for-renewables-grid-integration-challenges-and-technologies`

[82] R. Rosso, X. Wang, M. Liserre, X. Lu, S. Engelken, Grid-forming converters: An overview of control approaches and future trends, in: ECCE 2020 - IEEE Energy Conversion Congress and Exposition, 2020, pp. 4292–4299. `doi:10.1109/ECCE44975.2020.9236211`.

[83] Y. Lin, J. H. Eto, B. B. Johnson, J. D. Flicker, R. H. Lasseter, H. N. V. Pico, G.-S. Seo, B. J. Pierre, A. Ellis, Research roadmap on grid-forming inverters (2020).
URL `https://www.nrel.gov/docs/fy21osti/73476.pdf`

[84] K. Wang, Q. Song, B. Zhao, Z. Yu, R. Zeng, Grid-Forming Control of Offshore Wind Farms Connected With Diode-Based HVDC Links Based on Remote Active Power Regulation, IEEE Transactions on Sustainable Energy 15 (2) (2024) 1315–1327. `doi:10.1109/TSTE.2023.3343418`.

[85] ENTSO-E, Grid-Forming Capabilities: Towards System Level Integration (2021).
URL `https://vision2030.entsoe.eu/%0Ahttps://eepublicdownloads.entsoe.eu/clean-documents/RDCdocuments/210331_GridFormingCapabilities.pdf`

[86] V. Gevorgian, S. Shah, W. Yan, P. Koralewicz, R. Wallen, E. Mendiola, Grid-Forming Wind Power (ESIG Technical Workshop). National Renewable Energy Laboratory (2022).
URL `https://docs.nrel.gov/docs/fy22osti/82509.pdf`

[87] D. Pagnani, L. Kocewiak, J. Hjerrild, F. Blaabjerg, C. L. Bak, Integrating black start capabilities into offshore wind farms by grid-forming batteries, IET Renewable Power Generation 17 (14) (2023) 3523–3535. `doi:10.1049/rpg2.12667`.

[88] D. Pagnani, L. Kocewiak, J. Hjerrild, F. Blaabjerg, C. L. Bak, R. Blasco-Gimenez, J. Martínez-Turégano, Power system restoration services by grid-forming offshore wind farms with integrated energy storage, in: IEEE Power and Energy Society General Meeting, 2023, pp. 3–7. `doi:10.1109/PESGM52003.2023.10253374`.

[89] Ramboll, 2 Myths and an open question about water and Power-to-X (2025).
URL `https://www.ramboll.com/net-zero-explorers/green-hydrogen-and-power-to-x-water-myths`

[90] R. F. Service, Splitting seawater could provide an endless source of green hydrogen, Science 379 (6637) (2023). `doi:10.1126/science.adh8151`.

[91] J. Guo, Y. Zheng, Z. Hu, Direct seawater electrolysis by adjusting the local reaction environment of a catalyst, Nat Energy 8 (2023) 264–272. `doi:10.1038/s41560-023-01195-x`.

[92] M. A. Khan, T. Al-Attas, S. Roy, M. M. Rahman, N. Ghaffour, V. Thangadurai, S. Larter, J. Hu, P. M. Ajayan, M. G. Kibria, Seawater electrolysis for hydrogen production: A solution looking for a problem?, Energy & Environmental Science 14 (2021) 4831–4839. `doi:10.1039/D1EE00870F`.

[93] M. B. Abid, R. A. Wahab, M. A. Salam, I. A. Moujdin, L. Gzara, Desalination technologies, membrane distillation, and electrospinning, An overview, Heliyon 9 (2) (2023) e12810. `doi:10.1016/j.heliyon.2023.e12810`.

[94] IDE Technologies, Thermal Desalination Technologies (2025).
URL https://ide-tech.com/en/water-solutions/sea-water-desalination/thermal-desalination/

[95] F. Vassallo, C. Morgante, G. Battaglia, D. L. Corte, M. Micari, A. Cipollina, A. Tamburini, G. Micale, A simulation tool for ion exchange membrane crystallization of magnesium hydroxide from waste brine, Chemical Engineering Research and Design 173 (2021) 193–205. doi:10.1016/j.cherd.2021.07.008.

[96] A. Panagopoulos, V. Giannika, Decarbonized and circular brine management/valorization for water & valuable resource recovery via minimal/zero liquid discharge (MLD/ZLD) strategies, Journal of Environmental Management 324 (2022) 116239. doi:10.1016/j.jenvman.2022.116239.

[97] R. F. Service, Seawater could provide nearly unlimited amounts of critical battery material (2020). doi:10.1126/science.abd8037.
URL https://www.science.org/content/article/seawater-could-provide-nearly-unlimited-amounts-critical-battery-material

[98] IEA, Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5 C Climate Goal, Tech. rep., International Renewable Energy Agency, Abu Dhabi (2020).
URL https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction

[99] E. C. Wormslev, J. L. Pedersen, C. Eriksen, R. Bugge, N. Skou, C. Tang, T. Liengaard, R. S. Hansen, J. M. Eberhardt, M. K. Rasch, J. Höglund, R. B. Englund, J. Sandquist, B. M. Güell, J. J. K. Haug, P. Luoma, T. Pursula, M. Bröckl, Sustainable jet fuel for aviation - Nordic perspectives on the use of advanced sustainable jet fuel for aviation, Nordic Council of Ministers, 2016. doi:10.6027/TN2016-538.

[100] IRENA in partnership with Methanol Institute, Innovation outlook – renewable methanol (2021).
URL https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf?rev=ca7ec52e824041e8b20407ab2e6c7341

[101] A. Patonia, R. Poudineh, Ammonia as a storage solution for future decarbonized energy systems, Oxford Institute for Energy Studies, 2020.
URL https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/11/Ammonia-as-a-storage-solution-for-future-decarbonized-systems-EL-42.pdf

[102] V. Kyriakou, I. Garagounis, E. Vasileiou, A. Vourros, M. Stoukides, An electrochemical Haber-Bosch process, Nature Catalysis 2 (2019) 254–263. doi:10.1016/j.desal.2020.114569.

[103] J. Ikäheimo, J. Kiviluoma, R. Weiss, H. Holttinen, Power-to-ammonia in future north european 100% renewable power and heat system, International Journal of Hydrogen Energy 43 (2018) 17295–17308. doi:10.1016/j.ijhydene.2018.06.121.

[104] ALFA LAVAL, HAFNIA, HALDOR TOPSØE, VESTAS, SIEMENS GAMESA, Ammonfuel – an industrial view of ammonia as a marine fuel (2020).
URL https://www.topsoe.com/hubfs/DOWNLOADS/DOWNLOADS%20-%20White%20papers/Ammonfuel%20Report%20Version%2009.9%20August%203_update.pdf

[105] M. F. Rojas-Michaga, S. Michailos, E. Cardozo, M. Akram, K. J. Hughes, D. Ingham, M. Pourkashanian, Sustainable aviation fuel (SAF) production through power-to-liquid (PtL): A combined techno-economic and life cycle assessment, Energy Conversion and Management 292 (2023) 117427. doi:10.1016/j.enconman.2023.117427.

[106] K. Seymour, M. Held, B. Stolz, G. Georges, K. Boulouchos, Future costs of power-to-liquid sustainable aviation fuels produced from hybrid solar PV-wind plants in Europe, Sustainable Energy Fuels 8 (2024) 811–825. `doi:10.1039/D3SE00978E`.

[107] J. Boilley, A. Berrady, H. B. Shahrel, E. Gürbüz, F. Gallucci, Energy analysis of a power-to-jet-fuel plant, International Journal of Hydrogen Energy 58 (2024) 1160–1176. `doi:10.1016/j.ijhydene.2024.01.262`.

[108] Direção-Geral do Território, Carta de Uso e Ocupação do Solo - COS 2018 - RDF - Projeto Cross-Forest (2021).
URL `https://dados.gov.pt/en/datasets/carta-de-uso-e-ocupacao-do-solo-cos-2018-rdf-projeto-cross-forest-land-use-land-cover-map-cos-2018-rdf-cross-forest-project/`

[109] J. Barbosa, S. G. Simões, P. Oliveira, P. Patinha, L. Quental, J. Catarino, T. Simões, C. Rodrigues, P. J. R. Pinto, J. P. Cardoso, Distribuição do consumo de eletricidade na indústria no território em Portugal Continental e a potencial satisfação desta procura por fonte solar fotovoltaica, Tech. rep., LNEG, Amadora, Portugal (2023).
URL `http://hdl.handle.net/10400.9/4164`

[110] Agência Portuguesa do Ambiente, Registo de Emissões e Transferência de Poluentes (PRTR) (2025).
URL `https://apambiente.pt/avaliacao-e-gestao-ambiental/registo-de-emissoes-e-transferencia-de-poluentes-prtr`

[111] Agência Portuguesa do Ambiente, Dados prtr 2010–2023, `https://apambiente.pt/sites/default/files/_Avaliacao_Gestao_Ambiental/PRTR/dados-2010-2023.xlsx` (2025).

[112] European Hydrogen Observatory, Electrolyser cost (2025).
URL `https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/production-trade-and-cost/electrolyser-cost`

[113] DGEG, Preços de combustíveis em portugal continental (2025).
URL `https://www.dgeg.gov.pt/pt/estatistica/energia/precos-de-energia/precos-de-combustiveis-em-portugal-continental/`

[114] S&P Global, Platts ammonia price chart (2025).
URL `https://www.spglobal.com/commodity-insights/en/news-research/latest-news/energy-transition/051023-interactive-ammonia-price-chart-natural-gas-feedstock-europe-usgc-black-sea`

[115] METHANEX, Methanex posts regional contract methanol prices for Europe, North America, Asia and China (2025).
URL `https://www.methanex.com/about-methanol/pricing/`

LNEG

INVESTIGAÇÃO PARA A **SUSTENTABILIDADE**

ENERGIA E GEOLOGIA – CONSTRUINDO UM **FUTURO MAIS LIMPO E MELHOR**

X INSTAGRAM FACEBOOK LINKEDIN YOUTUBE

www.lneg.pt