European Commission

Study on the Offshore Energy Potential in the Atlantic Ocean

Final Report

Written by:
J. Dubranna, R. Fofack-Garcia (FEM)
C. Verrecchia, B. Rodrigues, S. Langiano (EDP NEW)
J. Berque (Tecnalia)
G. Iglesias, E. Laino, B. Alvarez (UCC)
[*July – 2023*]

EUROPEAN COMMISSION

Directorate-General for Energy
Directorate C — Green Transition and Energy System Integration
Unit C.4 — Infrastructure and Regional Cooperation

Contact: Michela Marasco

E-mail: Michela.Marasco@ec.europa.eu

European Commission
B-1049 Brussels

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Manuscript completed in July 2023

1st edition

Luxembourg: Publications Office of the European Union, 2023

PDF ISBN 978-92-68-07808-2 doi: 10.2833/754673 MJ-04-23-954-EN-N

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ABREVIATIONS AND ACRONYMS

AMETS Atlantic Marine Energy Test Site
AC/DC Alternating Current / Direct Current
CAPEX/OPEX CAPital Expenditure / Operational Expenditure
CBA Cost-Benefit Analysis
ECMWF European Centre for Medium-Range Weather Forecasts
EDP Energias de Portugal
FEM France Energies Marines
FOW Floating Offshore Wind
GHG GreenHouse Gas
IEA International Energy Agency
IFREMER French National Institute for Ocean Science
IRENA International RENewable Energy Agency
IUCN International Union for Conservation of Nature
LCOE Levelized Cost of Energy
MRE Marine Renewable Energy
MRIA Marine Renewables Industry Association
NEWA New European Wind Atlas
NSOG North Sea Offshore Grid
ORE Offshore Renewable Energy
OREDP Offshore Renewable Energy Development Plan
OSW Offshore Wind
PPE Pluriannual Energy Program
RES Renewable Energy Sources
RESS Renewable Electricity Support Scheme
SEAI Sustainable Energy Authority of Ireland
SHOM French Naval Hydrographic and Oceanographic Service
TSO/DSO Transmission System Operators / Distribution System Operators
UCC University College Cork
WEC Wave Energy Converter
WEI Wave Exploitability Index

EXECUTIVE SUMMARY

This document is reporting the Study on the offshore energy potential in the Atlantic Ocean carried out in response to the contract ENER/2020/OP/0028/C4/SER/2020-774/SI2.858799 issued by the Directorate-General for Energy of the European Commission.

Potential for offshore renewable energy generation

State of play

Offshore Renewable Energy (ORE) - including wind (bottom-fixed and floating), waves, tidal currents and floating solar PV – currently have a total installed capacity of 535 MW along the European Atlantic Arc Member States[1, 2]. With 54 projects ranging between the early planning to the operating stage, the ORE sector is undergoing strong development to support the European ambition to become carbon neutral by 2050. Offshore wind benefits from a more advanced technological development compared to the other ORE technologies, and 45 of the 54 projects are dedicated to that technology, with a planned total capacity of 35 GW to 38.5 GW. 28 projects are related with bottom-fixed solutions (about 17 GW), 15 with floating (about 13 to 14 GW) and 4 may mix fixed and floating solutions (4 GW). The other projects are shared between wave (4 projects) and tidal (5 projects) technologies - which work their way to reach commercial viability and scale. The tidal technical potential is estimated between 5.3 and 55 GW while wave energy is expected to be able to produce some 30 GWh of electricity per year and per km² of wave farm in the most promising areas. The current wave and tidal energy projects along the Atlantic Arc totalize a capacity of some 40 MW.

Identification of ORE technical capacity and suitable sites

After accounting for the technical and the major non-technical constraints (regulated/protected areas, other human activities), a set of 15 macro-scale areas suitable for offshore wind deployment is selected with a total capacity of about 2650 GW. They are extending up to 1000 m-depth, and would be suitable both for bottom-fixed (up to 50 to 100 m) and floating platform solutions (from 50 to 1000 m). Within these areas, 5 are in Ireland (46% of the capacity), 5 in France (38% of the capacity), 3 in Spain (8% of the capacity) and 3 in Portugal (8% of the capacity). In addition, the wind technical potential is highest and the competing interests with other usage of the sea are reduced in these areas and they are consistent with the Maritime Spatial Planning of each country (Ireland[3], France[4], Spain[5], [6] and Portugal[7]). For each country, an area suitable for benchmarking the economics of cross-border power exchanges is also highlighted.

For wave resource, the potential along the European Atlantic Arc is high. Ireland has the highest potential and 3 sites are identified on the West coast. In addition, 3 wave sites with significant but lower wave potential are proposed in France, 4 in Spain and 3 in Portugal.

[1] Republic of Ireland, France, Spain and Portugal
[2] Islands are out the scope of this study
[3] https://atlas.marine.ie/
[4] Planification des espaces maritimes : carte des vocations (arcgis.com)
[5] Visor INFOMAR - MITERD, CEDEX (miteco.es)
[6] https://map.4coffshore.com/offshorewind/
[7] https://webgis.dgrm.mm.gov.pt/portal/apps/webappviewer/index.html?id=df8accb510bc4f33963d9b03bf3674b8

Tidal resource, in the vast majority, is concentrated in the Irish Sea, along the English Channel coast of France, and in the Sea of Iroise. Ireland and France each have 4 favorable areas representing a total technical capacity potential ranging from 5.3 GW to about 55 GW depending on the minimum current velocity threshold used for the delimitation of the suitable areas. Spain and Portugal have comparatively low tidal potential due to limited tidal range.

Floating solar PV technology is in its early stage of development. The areas with higher potential are located to the southwest of France and offshore Portugal. As for Spain, the Mediterranean coast is expected to offer much more profitable solution than its Atlantic counterpart.

Identification of technical challenges
For deployments of offshore renewables to reach a scale where they should impact the design of offshore transmission infrastructure, the technology must advance to where deployments at depths of about 100 m are cost-competitive. For offshore wind, this may be achieved by incremental improvements to current jacket and monopile foundations, or by reducing costs for floating platforms. For the latter, important reduction in floater costs must be achieved, and crane operations between floating platforms must become more weather-resilient. Other marine energies such as tidal and wave, may mature into important coastal industries with many societal benefits, but are unlikely to reach the scale where they should impact offshore transmission design in the 2050 horizon. Offshore solar photovoltaics, while nascent technology still, may rapidly bring down costs of floating platforms, mooring/anchors and marine operations. In this case, deployments could in principle reach scales beyond those possible with offshore wind, but competition for marine space and ecosystem impacts would need to be managed.

Production scenarios

Task 2 addresses the definition of two offshore production scenarios for 2030 and 2050: the current pathway, and the ambitious scenario. The scenarios presented have two main considerations: capacity deployed by country and LCOE maps for the European Atlantic Arc. The maps deliver color-coded LCOE values for each technology on the macro-areas selected in Task 1. The LCOE analysis then shows that the countries with higher potential of deployment are also expected to reach lower LCOE values.
The production scenarios are defined by choosing as many production units with lowest LCOE as necessary to meet the capacity ambitions of the country.
The scenarios defined for the European Atlantic Arc result in a total of 14.3 GW and 76.7 GW of offshore renewable energy by 2030 and 2050 respectively on the current pathway scenario and 27.7 GW and 97.0 GW by 2030 and 2050 on the ambitious scenario.

Grid options

Task 3 defines two different options for grid connection for each of the proposed production scenarios, a radial grid and a hybrid-grid layout and benchmark the two via a CBA that takes into account parameters such as CAPEX, OPEX, social welfare, CO_2 emissions, ORE curtailment and ORE penetration in the energy mix.

All scenarios require considerable investments in offshore power generation and connection to the onshore grid. The total CAPEX of integrating 14.5 GW by 2030 in the current pathway scenario is around 40.3-40.6 billion €, whereas to integrate 27.8 GW by 2030 in the ambitious scenario is around 68-69 billion € depending on the grid option. This study shows how floating offshore wind would stand for 40-70% of the investments in offshore power generation, depending on the scenario, by 2030.

To achieve the RES integration of 76 GW in the current pathway scenario 2050 an investment of 144-145 billion € is required, that increases up to 180-182 billion € in the ambitious scenario, depending on the grid option, to integrate 96.5 GW.

For all production scenarios, the radial connection requires lower CAPEX and OPEX than the hybrid alternatives. The reason is that the hybrid alternatives require further cables to interconnect different production blocks. Nevertheless, CAPEX increase in this case is quite limited and sometimes compensated by socioeconomic improvements. On the downside, the radial alternatives provoke a decrease in security of supply, as the outage of a cable would mean the loss of its production block. However, the hybrid approach would require a bigger commitment in terms of policies as the whole group of production blocks should be realised as a common project.

For what concerns the hybrid alternatives, this study concludes that possible benefits exist in terms of increase of social welfare and CO2 emission savings. In particular, for the 2030 production scenarios, the hybrid approach would bring increase of the social welfare by roughly 183 M€/year in the case of the current pathway scenario and around 330-380 M€/year in the case of the ambitious scenario. The situation slightly changes for the ambitious scenario, where the hybrid approach is not beneficial for the current pathway scenario, as it leads to socioeconomic decrease estimated at around 5 M€/year, whereas in the case of the ambitious scenario, the hybrid approach results in an increase of the social welfare of 176 M€/year.

Finally, in all the production scenarios, the hybrid approach leads to higher CO_2 savings and lower ORE curtailments.

Implementation challenges and barriers

The key non-technical challenges to be overcome for improving planning, consenting processes and acceptability of ORE technologies are presented in this part.
Regulatory and administrative challenges, social-ecological challenges, economic and financial challenges, challenges related to Maritime Spatial Planning (MSP) and multi-use of the marine space, supply chain challenges. For each category, specific non-technical challenges are detailed, and a precise definition of specific challenges is provided. For each country, an analysis of the strategies to overcome the non-technical barriers is provided.

Identification of prime areas for offshore development

This section proposes a ranking exercise within the areas selected in previous tasks for offshore wind, solar, wave and tidal energy. A multicriteria approach is implemented to assign scores on a scale from 0 to 100, taking into account the levelized cost of energy (LCOE) and other uses of the marine space such as fishing, navigation, military areas, nature protected zones, oil & gas, communication cables, etc. Two sets of results are produced, corresponding to 2030 and 2050. The results are presented graphically on a series of maps to facilitate interpretation. Thus, the areas on which the first efforts for the development of offshore renewable energy in the European Atlantic should concentrate are highlighted.

INTRODUCTION

The European Green Deal[8] set out the policy initiatives of the European Commission to transform Europe into a climate-neutral continent by 2050. Towards this goal, the European 2030 climate target plan posited the need for reducing greenhouse gases emissions by at least 55% by 2030 relative to 1990 levels. The potential of offshore renewable energies to contribute to the decarbonisation process and support a modern, resource-efficient and competitive economy, with maritime occupation compliant with the EU Biodiversity Strategy[9], was also put forward by the Green Deal Communication in the framework of the European Green Deal. In sum, harnessing the vast ocean resources is a must in the plan for Europe to become climate neutral by 2050.

In this context, in November 2020, the European Commission adopted the offshore renewable energy strategy (ORES)[10], proposing an all-encompassing approach for the development and integration of offshore energy. The ORES is a policy cornerstone and the blueprint to ensure the success of large-scale offshore renewable energy planning and deployment.

The Strategy estimates that offshore renewable energy has a great potential to scale up from today's installed offshore wind capacity (14.6 GW) at least to the 60 GW target by 2030, complemented by 1 GW of ocean energy[11]. Installed capacities of at least 300 GW of offshore wind and 40 GW of ocean energy by 2050 are a realistic and achievable objective. Meeting this objective includes, in a limited period of time, putting in place and implementing an ambitious general enabling framework addressing barriers and challenges, to efficiently support the development of the ORE sector and related grid infrstructures. The investments needed to achieve these goals are estimated up to 800 billion €[12].

The EU ORES highlights the vast and varied offshore potential in all EU sea basins and the benefits of regional cooperation to successfully tap this potential. Regional cooperation has been stepped up in some sea basins, with the North Seas Energy Cooperation established in 2016 (NSEC) being a reference in terms of experience and good practices for Member States willing to jointly foster the development of offshore wind and address regulatory, economic and other barriers hindering the development of concrete cross-border projects. More recently, cooperation has intensified among countries in the Baltic Sea region where, following a political declaration committing to closer cooperation on offshore wind in the Baltic Sea, a specific work stream within the BEMIP (Baltic Energy Market Interconnection Plan) High Level Group adopted an Offshore Wind Work Programme, therefore operationalising this commitment. Additional cooperation initiatives have since started also in the other sea basins.

In this context, on 17th December 2020, the European Commission DG Energy opened a call for proposals for a study of the potential for a coordinated approach in the continental European parts of the Atlantic Ocean and the Republic of Ireland, in order to map their offshore energy potential and explore the optimal solutions to connect offshore renewable

[8] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en
[9] Eu Biodiversity Strategy for 2030. Bringing nature back in our lives. COM(2020)/380 final
[10] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12517-Offshore-renewable-energy-strategy_en
[11] European Commission (2020) – Progress of clean energy competitiveness – SWD(2020)/953 final
[12] JRC (2020) Facts and figures on Offshore Renewable Energy Sources in Europe, JRC121366

energy (ORE) generation with onshore grids, thus contributing to the decarbonisation objectives.

This call may be considered a continuation for the Atlantic Arc of previous studies on the Baltic and Mediterranean Seas. Consequently, the study will be guided substantially by their organization, outcomes and recommendations. In particular, the Mediterranean study focused on the benefits of a cross-border coordinated approach to overcome the barriers to offshore renewable energy development, addressing ORE potential and development, grid and spatial planning, financing cooperation, appropriate market and permitting conditions, and technology research, demonstration and innovation. These elements will also be considered for the Atlantic study.

In this context, the proposed study is expected to:

- Map the technical potential of offshore energy generation in the continental European parts of the Atlantic Ocean and the Republic of Ireland, taking into account the geographical and climatic conditions and the comparative assessment of potential generation technologies, notably offshore wind (including floating) and ocean energy (wave and tidal);
- Analyse the potential need for a hybrid offshore grid in the continental European parts of the Atlantic Ocean and the Republic of Ireland, including an assessment of costs and benefits for the participating countries;
- Create an inventory of legal, regulatory, financial and coordination challenges relating to cross-border offshore grid projects (including challenges related to the mapping of the continental shelves) that could be further looked into at a later stage;
- Assess the practical ORE potential considering implementation challenges, including environmental impacts and public acceptance;
- Lay down policy recommendations on measures to overcome the barriers to ORE development.

1. POTENTIAL FOR OFFSHORE RENEWABLE ENERGY GENERATION

This chapter first explores the current state of play of the offshore renewable energies along the European Atlantic Arc, then the potential for electricity generation from ORE is established for a set of macro-scale areas where both technical limitations and non-technical constraints are limited. Finally, the main technical challenges that need to be addressed to support the ambitions of ORE deployment are presented.

1.1. State of play of offshore renewable energy generation projects

1.1.1. European Atlantic Arc – All Offshore Renewable Energies considered

This section addresses the state of play of the past, ongoing and planned Offshore Renewable Energy (ORE) projects in the European Atlantic Arc Member States including offshore wind, wave, tidal and floating solar technologies for the Republic of Ireland, France, Spain and Portugal. In addition, the current and future installed capacity ambitions are presented. Note that the projects in Canary, Azores or Madeira islands are out of the scope of this study.

TABLE 1-1 : CURRENTLY INSTALLED ORE CAPACITY IN THE ATLANTIC ARC[13]

Area/Country	Total offshore wind [MW]	Bottom-fixed offshore wind [MW]	Floating offshore wind [MW]	Tidal energy [MW]	Wave energy [MW]
Atlantic Arc	**54.2**	**25.2**	**29**	**~100 kW**	**0.9**
Rep. of Ireland	25.2	25.2	0	0	0
France	2	480	2	~100 kW, pilot	0
Spain	2	0	2	0	0.9
Portugal	25	0	25	0	0

The ORE installed capacity along the European Atlantic Arc is currently limited to about 55 MW (Table 1-1) although the area benefits from high wind, wave and tidal resources as well as from an extensive maritime territory. Existing offshore capacity mainly consists of small demonstration/pilot farms with capacities in the order of tens of MW at most for offshore wind (Ireland and Portugal). France and Spain both have a 2-MW floating turbine in demonstration at their SEM-REV and BiMEP ORE test facilities respectively. France is the only country with significant tidal projects, mainly in the testing/pilot stage, and operates one offshore test site specifically dedicated to tidal energy. Spain has built significant experience in wave energy by operating the Mutriku power plant since 2011 (300 kW) and the BiMEP test facility where Wello's technology (600 kW) is currently being tested. The WaveRoller (350 kW) unit has undergone a 2-year testing period in Portugal and was decommissioned in 2021. Tidal and wave energy in the European Atlantic Arc are yet to reach commercial viability. Offshore floating solar development is currently inexistant in the European Atlantic Arc.

[13] Including testing facilities

Although their capacity is currently limited, ORE are expected to play a key role in the decarbonisation of the energy production, whatever the scenario to transform Europe into a climate-neutral continent by 2050. The EU has great potential to scale up from the 12 GW of installed offshore wind capacity in 2020 to at least 60 GW target by 2030, complemented by 1 GW of ocean energy. Ambitions of at least 300 GW of offshore wind and 40 GW of ocean energy by 2050 are set, provided appropriate regulation is decided and supportive measures are taken. The European countries of the Atlantic Arc are taking their share of the decarbonization effort by having a large number of ORE projects in progress[14], 54 projects in total plus uncounted (very recent) offshore wind projects in Portugal (Durakovic, 2022a)[15], more than 45 of which are dedicated to offshore wind (Table 1-2). The total capacity of ongoing/planned offshore wind projects reaches about 40 GW, combining both fixed (27 to 31 projects) and floating technologies (14 to 18 projects). 33 of them are in the early planning stage and have yet to be awarded, most of them in Ireland (30 projects) and France (3 projects), for a total of more than 30 GW. Ireland has an additional 330 MW of commercial-scale wind farm project which has been awarded. Still, offshore wind development in Ireland is linked to grid and export cables since its potential is higher than the national needs. 8 offshore wind projects are under construction for a total of about 2.9 GW fixed offshore wind in France (7 commercial projects). The energy crisis deriving from Russia'sweaponising of energy as part of its war of aggression against Ukraine has been a contributing factor in postponing and more than doubling the capacity target of the first offshore wind auction in Portugal. This operation, which was initially planned in summer 2022 and would award 3 to 4 GW of capacity, was eventually postponed to the last quarter of 2023 for 10 GW of installed capacity by 2030. As for Spain, the first offshore wind auction is expected to be in the Canary Islands region in 2023 for the deployment of 3 GW by 2030, in line with the Spanish Offshore Wind Roadmap approved in December 2021[16].

Wave and tidal energy are still in the process of reaching the commercial viability and scale. Ireland ambitions to deploy 2 wave energy pilot farms (5 MW each) around 2026 while the construction of a 4 x 300kW demonstration farm is about to start in Portugal. France has awarded the installation of 12.5 MW of tidal devices (2 projects) and additional 18.6 MW will be distributed over 3 farms as pilot/demonstration projects in the near future. There is no ongoing or planned offshore solar energy projects in the European Atlantic Arc.

[14] From early planning to operating stage

[15] https://www.offshorewind.biz/2023/01/24/portuguese-government-working-towards-planned-2023-offshore-wind-tender/

[16] Islands are outside the scope of the study

TABLE 1-2 : EXPECTED ORE CAPACITY FOR THE ONGOING PROJECTS[17] IN THE ATLANTIC ARC

Area/Country	Total number of offshore wind projects / Capacity [MW]	Number of bottom-fixed offshore wind projects / Capacity [MW]	Number of floating offshore wind projects / Capacity [MW]	Number of tidal energy projects / Capacity [MW]	Number of wave energy projects / Capacity [MW]
Atlantic Arc	**45 / 35073.5 to 38503.5**	**27 / 16893 (+4 / 4000 mixed fixed and floating or unspecified)**	**14 / 13180.5 to 14180.5 (+4 / 4000 mixed fixed and floating or unspecified)**	**5 / 31.1**	**4 / 11.2 + ~MW-scale**
Rep. of Ireland	32 / 28780 to 29710	19 / 13380 to 14310 (+3 / 3000 mixed fixed and floating)	10 / 12400 (+3 / 3000 mixed fixed and floating)	0 / 0	2 / 10
France	12 / 5291.5 to 5791.5	8 / 3513 (+1 / 1000 unspecified techno)	3 / 778.5 to 1278.5 (+1 / 1000 unspecified techno)	5 / 31.1	0 / 0
Spain	1 / 2	0 / 0	1 / 2	0 / 0	1 / ~MW-scale
Portugal	/ 10000	N/A	N/A	0 / 0	1 / 1.2

1.1.2. Wind energy

The first European offshore wind farms were inaugurated in the early 90's. By the end of 2020, Europe presented a total of 14.5 GW of installed capacity distributed over 11 countries (UK is excepted). Germany, Belgium, the Netherlands and Denmark are currently the European leaders in offshore wind electricity generation, which is exclusively produced by fixed offshore wind farms. The floating wind technology is currently at the pre-commercial development stage and the commercial stage is about to be achieved, with the first projects being at the call for tender stage.

1.1.2.1 Republic of Ireland

In Ireland, the focus on the wind resource exploitation has switched between onshore to offshore recently, thus the Irish Offshore Wind (OSW) industry is still in its infancy. In fact, there is only one operational offshore wind farm in Ireland at present: the 25.2 MW Arklow Bank Wind Park off the eastern coast.
However, the potential of this technology is high due to the extensive Irish maritime territory and the vast availability of the offshore wind resource on it. For instance, the Ireland's Offshore Renewable Energy Development Plan[18] (2014) indicated that the OSW potential which wind farms can develop without likely significant impacts on the environment is circa 34.8-39 GW. Furthermore, the expectancy in the OSW development has increased in the Programme for Government in 2020 compared to the projections given in the Climate Action Plan[19] (2019), to 5 GW by 2030 and the ambitions to develop tens of gigawatts into the future – e.g., the government has indicated that 30GW of FOW could be

[17] Projects from early planning stage to under construction
[18] https://www.gov.ie/en/publication/e13f49-offshore-renewable-energy-development-plan/
[19] https://www.gov.ie/en/publication/ccb2e0-the-climate-action-plan-2019/

developed off the west coast –. The previous targets are in accordance with the EirWind[20] project findings (2020), that indicate that 6.5-7.3 GW are achievable by 2030 and there is market room for up to 25 GW of OSW, considering a number of plausible development scenarios for existing electricity transmission and future green hydrogen production.
In fact, plans are underway for the extension of the Arklow Bank project, which has been consented for a minimum total installed capacity of 520 MW and could be commissioned in 2025. Furthermore, in May 2020, seven bottom-fixed OSW projects were given 'relevant project' status in the context of the forthcoming Marine Planning and Development Management Bill to be enacted – Oriel Windfarm, Dublin Array (Bray and Kish Banks), Codling Bank (Phase 1 and Phase 2), North Irish Sea Array, and Skerd Rocks –, adding up to 3.26 GW. Finally, other twenty-four OSW projects are at early planning or concept stage, accounting for an overall potential of 25.93 GW.
Further details about the operating and ongoing offshore wind projects in the Republic of Ireland are presented in Appendix1.

1.1.2.2 France

The first call for tenders for commercial offshore wind farms in France has been launched in 2010 and currently, six fixed offshore wind farms are under construction, cumulating a total of 2.9 GW of installed capacity. Two of them are located along the Atlantic coast, one is in the north of Brittany and three in the English Channel. These wind farms shall be in operation between 2022 and 2024. In addition, consenting has been given for a 600 MW fixed wind farm offshore of Dunkirk. Operation is expected to start in 2026.
The Floatgen demonstration project operates one 2 MW floating wind turbine using a floater based on Ideol's Damping Pool® technology at the SEM-REV test sit, since September 2018.
Three wind farm projects, floating or fixed and cumulating a total of 2.25 to 2.75 GW of installed capacity are in the early planning stage. The deployment areas are in Normandy, South of Brittany and offshore of Oléron island, and the consortium should be awarded in 2022 at the earliest.
Additional floating wind farm projects are in progress or planned in the Mediterranean Sea, with three pilot plants for 84 MW in total and two commercial projects for a total of 250 MW each with extension of 500 MW already foreseen.
France is currently facing an acceleration in the development of offshore wind farms and long-term planning becomes a necessity to better engage future deployments. Calls for tender of 2 GW per year on average are expected to be integrated in the next Pluriannual Programming of Energy that will be released in 2023.
Further details about the operating and ongoing offshore wind projects in France are presented in Appendix 1.

1.1.2.3 Spain

Spain's offshore wind energy potential is in the tens of gigawatts but so far has not been exploited. The fundamental reason is geology: a combination of alpine orogeny to the north, south and east, and one of the largest remaining older, variscan orogeny on the western seaboard, is belting the country with narrow continental shelves of rapidly increasing depth. As an aside, these same geological drivers have bestowed the country with countless mountain ridges, excellent for onshore wind deployment, helping make the country a world leader in wind power production and technology. At any rate, thus unsuitable for large bottom-fixed deployment, the country had to wait for advances in floating wind technology – essentially, a drop in platform costs together with larger turbine

[20] https://www.marei.ie/project/eirwind/

– for perspective to open offshore. This, according to many industry observers, is precisely what is happening at the moment. Hence, the coming years could see the announcement of large-scale offshore wind deployment in Spain. The first offshore wind auction is expected to be in the Canary Islands region in 2023 for the deployment of 3 GW by 2030, in line with the Spanish Offshore Wind Roadmap approved in December 2021[21].
At the moment however, there are few projects that have actually been floated. Let's mention Esteyco's Elisa project, with support including the EU's Horizon 2020 Program, of an innovative support structure, which was deployed in PLOCAN, Gran Canaria, in the late 2010s. In addition, SAITEC's 2 MW DEMOSATH floating wind turbine should also be deployed in Northern Spain in the summer of 2022.
Further details about the operating and ongoing offshore wind projects in Spain are presented in Appendix 1.

1.1.2.4 Portugal

During the last decades several R&D and demonstration projects were conducted to validate the economic and technical viability of the offshore wind energy in the Portuguese national waters.
The WindFloat 1 Project involved the development and construction of a demonstration unit, using a 2 MW commercial turbine. The unit was installed on the Portuguese coast, near Aguçadoura, and it was connected to the grid at the end of December 2011. Windfloat 1 operated for five years with high availability, producing more than 17 GWh, in a sea with waves of more than 7 meters and remaining operational even with waves of 17 m, demonstrating its technical and economic viability in the harsh Portuguese waters.
After successfully testing the technology for five years, through the WindFloat1 project, the next step in the development of WindFloat technology was the pre-commercial phase, called WindFloat Atlantic (WFA), the first floating wind power plant in continental Europe. To support the development of this pioneering technology, the European Investment Bank (EIB) granted, in October of 2018, a loan of 60 million euros to Windplus SA, the company that develops the WindFloat Atlantic, and which is owned by Ocean Winds (OW) (54.4%) – a joint venture between EDP Renováveis and Engie -, Repsol SA (19.4%) and Principle Power Inc. (1.2%). In addition, the project was also supported with 29.9 million euros from the EU program, NER300, and up to 6 million euros from the Government of Portugal, through the Portuguese Carbon Fund. The WFA consists in three floating wind turbines, with a cumulative capacity of 25 MW, located in Viana do Castelo, 20 km far from the shore where the water reaches a depth of 100 meters. The entire plant became operating in 2020, and since then it reaches 75 GWh of green energy produced in the first year.
As for the future projects, the energy crisis deriving from Russia's weaponising of energy as part of its war of aggression against Ukraine has been a contributing factor in postponing and doubling the capacity target of the first offshore wind auction in Portugal. This operation, which was initially planned in summer 2022 and would award 3 to 4 GW of capacity, was eventually postponed to 2023 for a capacity of 10 GW installed by 2030.
Further details about the operating and ongoing offshore wind projects in Portugal are presented in Appendix 1.

[21] Islands are outside the scope of the study

1.1.3. Wave energy

1.1.3.1 Republic of Ireland

Ireland is in a leading position to benefit from wave energy technologies thanks to the high-energetic wave climate on its extensive waters. According to the Irish Marine Institute[22], the wave energy resource potentially available to Ireland is estimated to be 21 TWh, which could meet 75% of the annual power demand; or 31 GW, according to the Offshore Renewable Energy Development Plan 1 (OREPD 1).

Although the wave energy potential is high in Ireland, commercial-scale projects have not been developed yet. However, there are two offshore test facilities at the moment: the ¼ scale wave energy test site in Galway Bay and the Atlantic Marine Energy Test Site (AMETS) project; and two full-scale demonstration projects still in development: the Saoirse project and the ESB Westwave project.

The Galway Bay ¼ scale Wave Energy Test Site is located 1.5 km offshore in water depths ranging from 20-23 m. The license for the site has been held by the Marine Institute since 2006. The research infrastructure on the site has recently been upgraded with the Galway Bay Sub Sea Cable Observatory, providing a cabled national test and demonstration facility for marine energy and technology.

The AMETS is a wave energy test site being developed by Sustainable Energy Authority of Ireland[23] (SEAI) in accordance with the national Offshore Renewable Energy Development Plan, as an integral component of Ireland's Ocean Energy Strategy to facilitate testing of full-scale wave energy converters in an open ocean environment.

The ESB Westwave project is a 5 MW wave energy project currently being developed near Doonbeg in Co Clare by ESB.

Saoirse is a full-scale wave energy conversion test and demonstration project being developed by Simply Blue Energy 4 km off the west coast of Clare, which will consist of a 5 MW wave energy conversion array of approximately 15-16 WEC units.

Further details about the operating and ongoing wave energy projects in the Republic of Ireland are presented in Appendix1.

1.1.3.2 France

France benefits a high wave energy potential along the Atlantic and the English Channel coastlines. The development of the SEM-REV test site by Ecole Centrale de Nantes was initiated in 2007 to support, as a first step, the wave energy conversion research and industry (certification in 2011). Following its certification for the testing of floating wind turbines in 2013, it now offers the possibility to connect 3 different devices/technologies to the grid at the same time. It is the 1st European offshore and multi-technology test site.

The last significant event in wave energy conversion occurred when Geps-Techno successfully tested its 150 kW wave energy prototype based on the point absorber principle at the SEM-REV test site, between 2019 and 2021.

All other developments are still at low TRL level, supported by basin testings.

Further details about the operating and ongoing wave energy projects in France are presented in Appendix1.

1.1.3.3 Spain

The Atlantic coast of Spain is exposed to swell generated by mid-latitude storms over the North Atlantic and Bay of Biscay. Wave resource is thus generally good, especially in the

[22] https://www.marine.ie/Home/home

[23] https://www.seai.ie/

Northwest corner of the Peninsula in Galicia, where flux is often above 40 kW per linear meter of coast, decreasing to some 25 kW eastward along the northern coast. The challenges for developers is not lack of wave resource, but rather the cost of enduring winter storms. Outside the Peninsula in the Canary Islands, the situation is more favourable from this point of view, with a less intermittent resource of remote-generated swell and no costly winter storm.
The Mutriku wave power plant holds the world record of wave energy production, crossing over 2 GWh produced in 2020. It is a shoreline plant embedded in the breakwater protecting the port of Mutriku. Its 18 oscillating water columns, with a total capacity of 298 kW, have been in operation since commissioning in 2011. Power take-off is mostly with Wells type of bidirectional turbines, though biradial turbines have been fitted for research purposes with promising results. There has been a number of other prototype projects in various areas of Spain. The IDOM/Oceantec floating oscillating water column holds another record, of survival this one, having operated through winter storms of significant wave height over 7 m. This 70 kW device, now decommissioned, was deployed in the Biscay Marine Energy Platform (BiMEP) in the late 2010s.
Further details about the operating and ongoing wave energy projects in Spain are presented in Appendix1.

1.1.3.4 Portugal

The waters of Portugal mainland have been used for testing multiple prototypes of offshore wave energy since 2004 and as early as 1999 in the Açores archipelago with the "Central de Ondas do Pico". The two main tests sites for demonstrations (TRL 8-9) are in the north of the country in Aguçadoura and Viana do Castelo.
In 2018, CorPower had a successful testing period of a 1:2 scale Wave Energy Converter (WEC) that provided important insights for the development of its technology. CorPower HiWave-5 project envisions to deploy its first commercial-scale 300 kW WEC (C4) in 2022 on the coast of Aguçadoura. After the successful installation of C4, the deployment of three full scale C5 WECs by 2023 is planned to form a pilot array and secure type certification.
According to Portugal's Plan for Energy and Climate to 2030, it is estimated a total installed capacity of wave energy in Portugal of 30 MW by 2025 and 70 MW by 2030[24].
Further details about the operating and ongoing wave energy projects in Portugal are presented in Appendix1.

1.1.4. Tidal energy

1.1.4.1 Republic of Ireland

Tidal energy is of particular interest to Ireland as its seas have been identified as major potential producers of wave and tidal energy. The Marine Institute indicates that the Irish tidal resource is concentrated off the East Coast, and that the tidal flow is relatively strong entering the Irish Sea, in St. George's Channel and the North Channel.
In Ireland, the wide-scale commercial use of tidal power is still several years off, although progress is positive and advancing quickly by several universities, research institutions and private companies.

[24] https://www.corpowerocean.com/projects/hiwave-5/

1.1.4.2 France

France offers 2 tidal energy test sites which are operated by the SEENEOH consortium[25]. The Bordeaux river site was inaugurated in 2018 and is dedicated to intermediate scale prototypes. The Paimpol-Bréhat site has been operating for more than 10 years and is appropriate for the testing of full-scale turbines. Both sites are connected to the grid.
Five tidal energy projects are planned for pilot or demonstration.
The earliest should be deployed in 2022 in the Fromveur straight by Sabella as 2 x 500 kW bottom-fixed turbines in the frame of the PHARES project[26], which mixes wind, tidal and solar energy, and storage capacity to feed Ushant island with electricity.
After one year of successful testing of its 1 MW, vertical axis tidal turbine at Paimpol Bréhat test site, Hydroquest is planning to deploy a pilot farm with 7 x 2.5 MW turbines in the Raz Blanchard by 2025[27].
Atlantis is also planning the deployment of 4 x 3 MW tidal turbines in Raz Blanchard as a pilot project within NormandyHydro consented area by 2025[28].
Finally, Minesto is planning to connect its kite technology demonstrator (100 kW) at Paimpol-Bréhat test site from May to August 2022 in the frame of TIGER project. This project also supports a future deployment of 2x250 W tidal turbines from Sabella in the Gulf of Morbihan.
Further details about the tidal energy projects in France are presented in Appendix1.

1.1.4.3 Spain

Aside from limited potential in a few inlets and estuaries, tidal currents are generally too weak in Spain to expect large tidal deployments. Geology is again the main driver. While tidal range is appreciable in the Atlantic seaboard (some 4-5 meters), narrow continental shelves prevent the excitation of significant tidal energy on these coasts.
The one exception is the Gibraltar straits, where currents represent a hydrokinetic potential which has been evaluated at over 7 GW. However, for environmental, shipping and other reasons, it is unlikely to see significant deployments.

1.1.4.4 Portugal

In Portugal only some low TRL studies had been done for tidal energy, none of them with an offshore perspective. According to Portugal's Plan for Energy and Climate to 2030, it is not predicted any investment in such technology for the near future (2030).

1.1.5. Floating solar photovoltaics

There are many technical challenges to overcome before offshore solar energy becomes competitive for deployment at utility-scale. However, the rapid pace at which inland floating solar has become competitive is now driving increased interest in its offshore potential. Some 100 MW of panel can be installed per hectare of floating farm, with a mean production expected of some 10-20 W/m2 on a yearly average. This compares to some 3 W/m2 for offshore wind farms, though unlike floating PV, the actual footprint of turbines is a small fraction of the farm's acreage. Should costs become competitive, and good environmental/biodiversity practices be developed, it would be an attractive renewable option for important load centres in coastal areas.
The overwhelming majority of projects for offshore solar are photovoltaic technology (PV). Some offshore concentrated solar power (CSP) projects had been considered until a few years ago, but rapid progress in onshore floating PV seems have focussed the attention

[25] https://seeneoh.com/
[26] https://www.akuoenergy.com/fr/phares
[27] https://www.hydroquest.fr/fermes-pilotes-hydroliennes/
[28] https://simecatlantis.com/projects/raz-blanchard-alderney/

away from floating CSP Rapid cost reduction of onshore CSP in recent years may however change this situation again.

1.1.5.1 Republic of Ireland

The potential of floating solar photovoltaic energy and the development of its technology at a commercial scale are still at a premature stage in Ireland, although the supporting of this emerging marine renewable energy solution is a strategic priority for Ireland to meet the targets of the Climate Action Plan 2019.

1.1.5.2 France

Despite a growing interest of some companies towards this technology, France has not planned any offshore solar energy project by now. However, France is home to the leading supplier of floaters and systems for onshore floating solar and may make rapid progress if and when interest rises. Resource would be best in the Mediterranean, Islands and outermost regions, but the Atlantic offshore southwest France may be interesting as well.

1.1.5.3 Spain

In the last few years, onshore floating solar has seen utility-driven, commercial deployment at the multi-megawatt scale in Spain. While the cost is near-competitive onshore, offshore deployment presents many challenges which for the moment have only begun to be addressed in research projects and prototypes. One example is the deployment by Branka, a materials technology company, and Tecnalia, of prototype concrete floaters in the port of Mutriku (Figure 1). While only partly exposed to ocean swell, wave excitation was still far more challenging than in inland deployments, indicating, among other things, a need for significant improvement in fatigue resistance of mechanical connection between floaters.

FIGURE 1 : BRANKA AND TECNALIA'S PROTOTYPE CONCRETE SOLAR FLOATERS IN MUTRIKU (SOURCE: TECNALIA)

Increased deployment is conditional to improvement in technology and good environmental/biodiversity practices. It is likely that the Mediterranean and Canary Islands would see such deployment first, should they occur, because of better insolation and less challenging winter storms. But important deployments on the Atlantic coast of southwest Spain are a possibility.

1.1.5.4 Portugal

Although there it the possibility of some exploratory projects for such technologies, Portugal does not currently have planned the development and installation of offshore solar energy.

1.2. Identification of offshore renewable energy potential spots

1.2.1. Wind energy

Wind is the most promising source of offshore renewable energy as far as the Gigawatt-scale farms are concerned. This part aims at presenting the technical potential of offshore wind energy, which are assessed by the compilation of spatially resolved information regarding the wind resource, wind-based electricity production and additional constraint layers that limit the potential of offshore wind deployment.

1.2.1.1 Average wind speed

The average annual wind speed at 100 m over the study area was retrieved from the Global Wind Atlas[29], at a resolution of 250 m, then degraded to a resolution of 1/60° to match the resolution of the bathymetric grid. Considering the current trend of the wind turbine size, a hub height of 150 m is expected to become the standard in 2030 and using 100 m may feel somewhat conservative. Choosing 150 m instead of 100 m as adopted in this report and assuming a log-profile, the average wind speed would be increased by 3 % to 3.3 %.
The wind speeds are available over the land and up to 200 km offshore, which is consistent with the Study on the Offshore Grid Potential in the Mediterranean Region (Konstantin Staschus et al., 2020b). The results are presented in Figure 2.

1.2.1.2 Technical constraints and technical potential

The offshore wind technical potential is an estimate of the generation capacity that is technically feasible, considering only the water depth and the resource limitations. These considerations were complemented by the necessity to be within the EEZ of the countries of the European Atlantic Arc State Members and/or at a distance from shore below 200 km, whichever is closer to the shore.

Depth limitations
Water depth is the main technically constraining element and the choice of the wind technology (fixed or floating) highly depends on it.
It is assumed that floating wind solutions will be installed at depths that fixed foundations cannot reach for technical or economic reasons, typically deeper than 50 to 60 m. However, the depth boundaries between fixed and floating wind farms are being blurred with fixed foundations targeting depths over 50 m (the Inch Cape offshore wind farm will use monopile foundations for depths up to 55 m). In addition, the maximum depth for floating offshore wind is being continuously increased from 60m some years ago, to the 100 m-range at present, up to 1000 m (possibly as much as 2500 m according to J. O'Flynn, (O'Flynn, 2022)) if massive efforts are put to lift the technical barriers, bring down the costs

[29] https://globalwindatlas.info/

to market level and give access to the very large wind potential at depths inaccessible to fixed offshore wind.

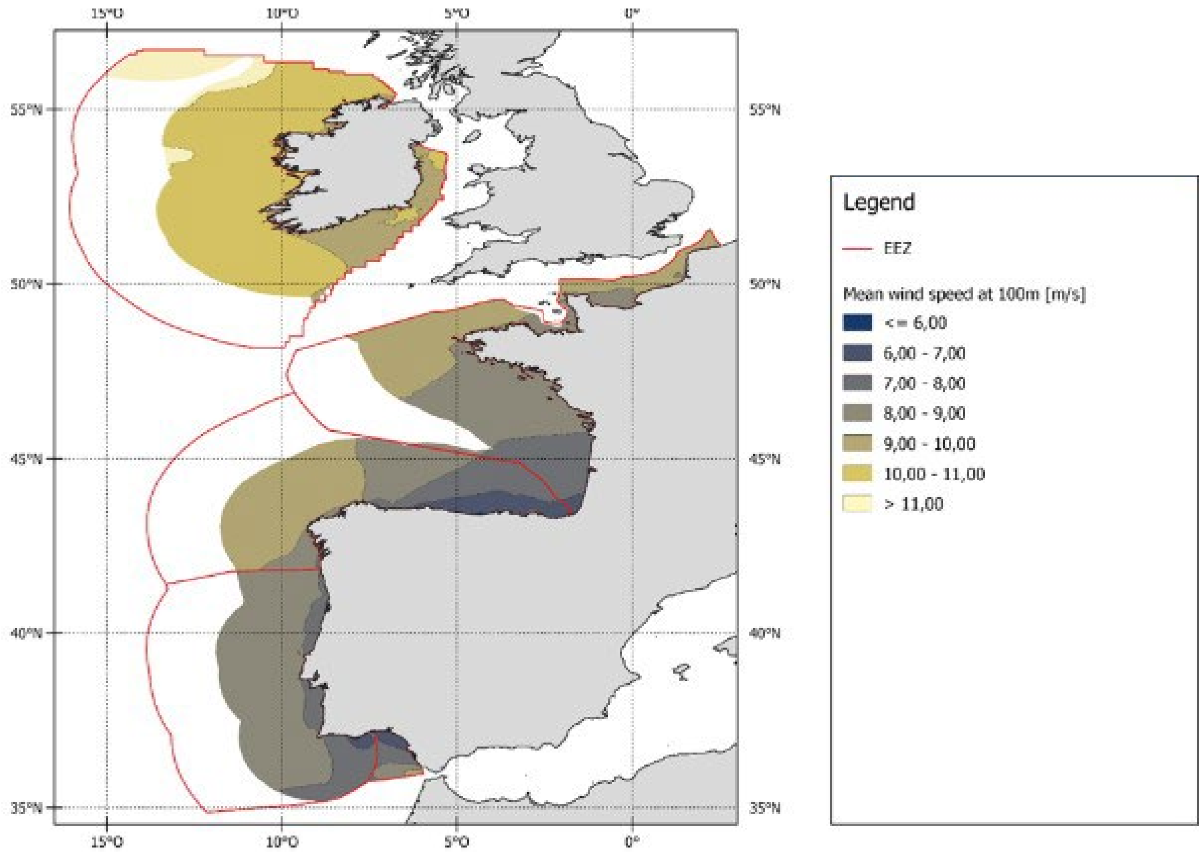

FIGURE 2 : MEAN WIND SPEED AT 100 M [M/S]

The depth boundaries chosen in the current report are expected to reflect the different technical limitations:

- 0 to 50 m – Suitable for fixed technology
- 50 to 100 m – Transitional depth, suitable for fixed and floating technologies
- 100 to 200 m – Suitable for floating technology only
- 200 to 1000 m – Suitable for deep floating technology

The areas corresponding to the bathymetric ranges and the suitable offshore wind technologies are presented in Figure 3. Note that Figure 3 extends up to the EEZ limits whereas our study area only extends from the shore up to 200 km offshore. This assumption was made to be consistent with the offshore limit and capacity density used in the Mediterranean study (Konstantin Staschus et al., 2020b).

Low resource limitations

The areas where the resource is too low are not expected to be economically viable and should be withdrawn from the technical potential assessment. For the wind power to be harvested in economically viable way, the minimum average wind speed at 100 m was set to 7.5 m/s based on Wind Europe's report choice (WindEurope, 2017), which would correspond to 7.75 m/s at 150 m assuming a log-profile of the wind speed. This is slightly lower than the 8 m/s limit at 150 m used for the Mediterranean study. The corresponding area is presented in Figure 3.

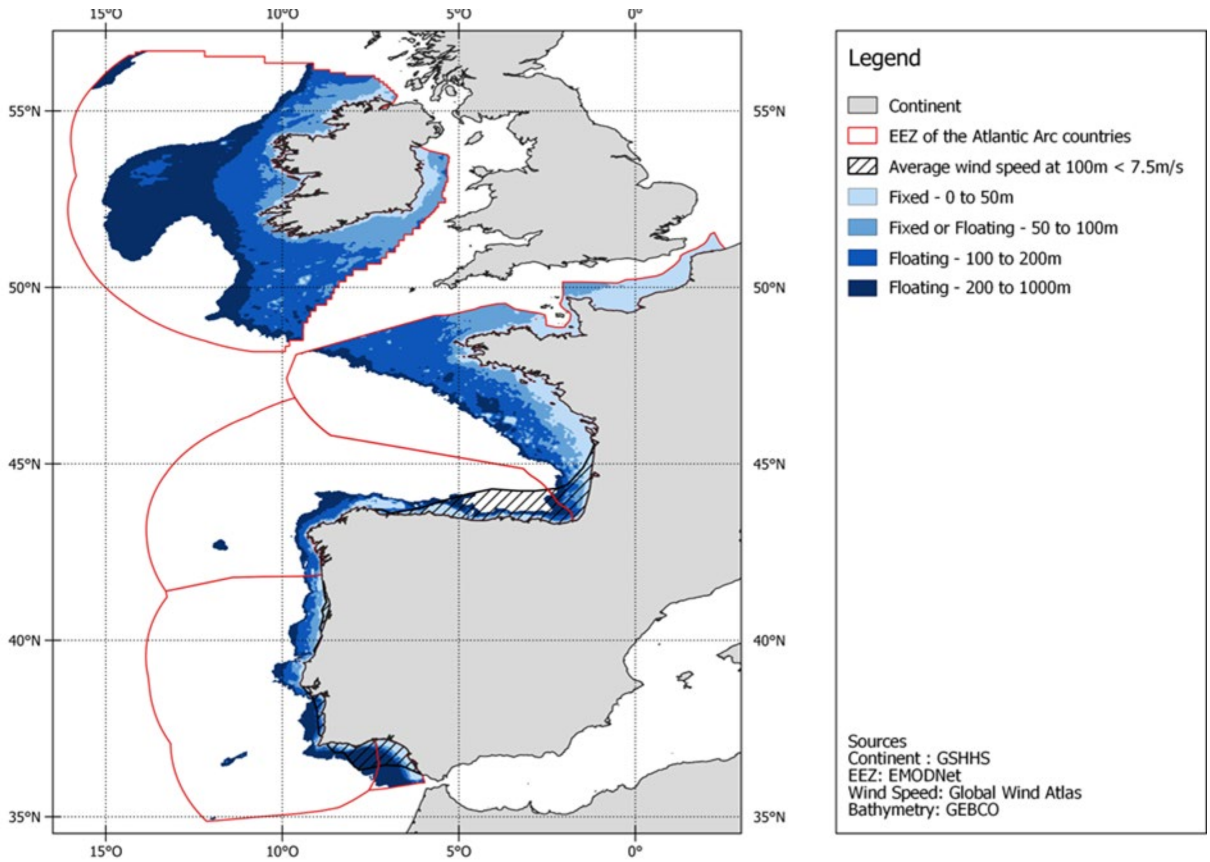

FIGURE 3 : TECHNOLOGY-DEPENDENT AREAS SUITABLE FOR THE DEPLOYMENT OF OFFSHORE WIND

The surface suitable for the deployment of offshore wind along the European Atlantic Arc when the depth- and resource-related constraints are considered are presented in Table 1-3. The losses related with insufficient resource are presented in Table 1-4, where the percentages are given relatively to the surface potential when the resource limitations are not considered.

TABLE 1-3 : SURFACE SUITABLE FOR OFFSHORE WIND DEPLOYMENT ALONG THE EUROPEAN ATLANTIC ARC [KM²]

Area/Country	Fixed, 0 to 50 m	Fixed or Floating, 50 to 100 m	Floating, 100 to 200 m	Floating, 200 to 1000 m	Total
Atlantic Arc	**72809**	**83612**	**139164**	**83564**	**379149**
Rep. of Ireland	19067	42738	68701	45175	**175680**
France	45137	32570	54865	11333	**143905**
Spain	5301	2515	7787	14734	**30337**
Portugal	3304	5789	7812	12322	**29277**

TABLE 1-4 : PERCENT OF SURFACE LOSSES DUE TO INSUFFICIENT RESOURCE

Area/Country	Fixed, 0 to 50 m	Fixed or Floating, 50 to 100 m	Floating, 100 to 200 m	Floating, 200 to 1000 m
Atlantic Arc	**18.2%**	**6.7%**	**4.8%**	**13.6%**
Rep. of Ireland	0.0%	0.0%	0.0%	0.0%
France	7.1%	6.8%	3.8%	8.2%
Spain	63.4%	47.9%	29.2%	33.3%
Portugal	51.8%	18.8%	16.6%	27.9%

Technical capacity potential

After retrieving the surface suitable for the deployment of offshore wind, a capacity density of 7 MW/km² was chosen for this study, both for the fixed and floating technologies. This assumption was made to be consistent with the offshore limit and capacity density used in the Mediterranean study (Konstantin Staschus et al., 2020b).

The resulting technical capacity potential for the European Atlantic Arc and for the Member States are presented in Figure 4 and Figure 5 respectively. The corresponding numbers are presented in Table 1-5.

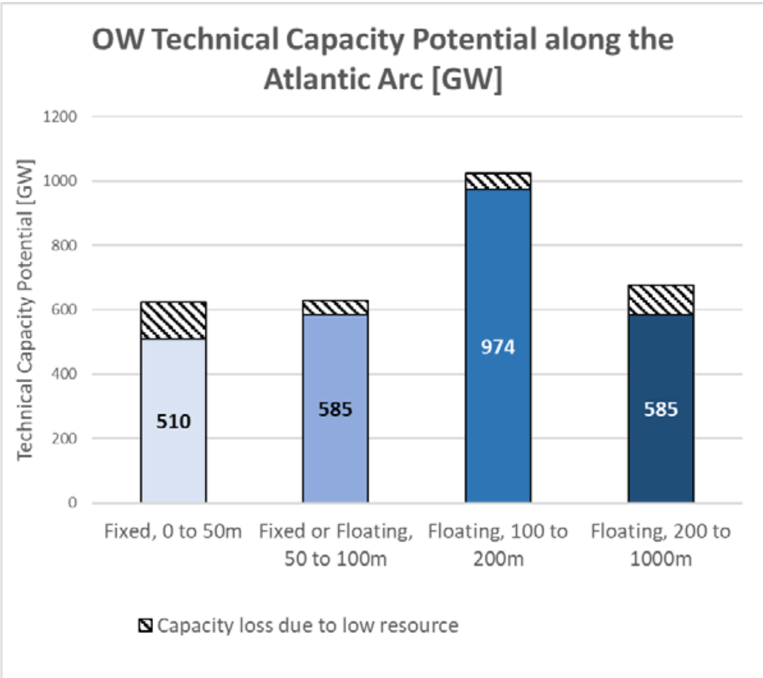

FIGURE 4 : TECHNICAL CAPACITY POTENTIAL ALONG THE EUROPEAN ATLANTIC ARC [GW]

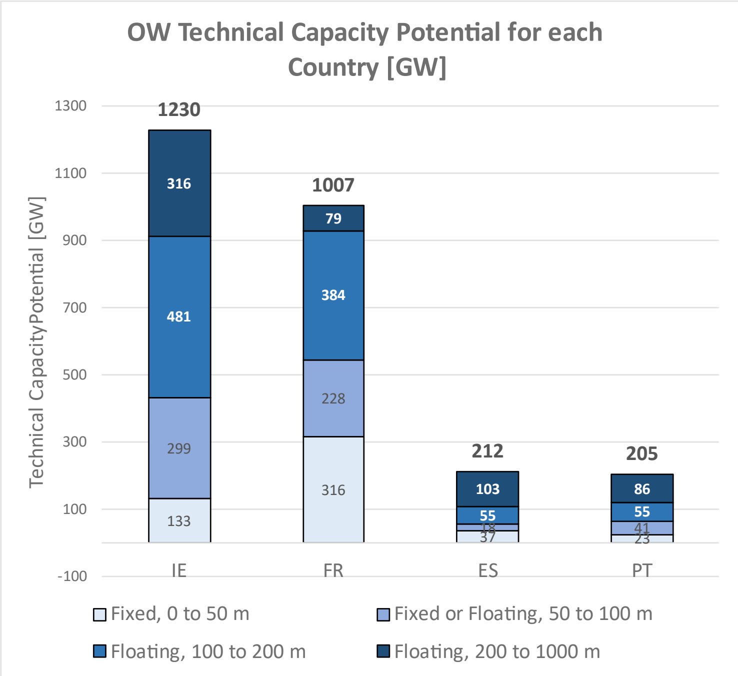

FIGURE 5 : TECHNICAL CAPACITY POTENTIAL FOR THE MEMBER STATES OF THE EUROPEAN ATLANTIC ARC [GW]

TABLE 1-5 : TECHNICAL CAPACITY POTENTIAL FOR THE EUROPEAN ATLANTIC ARC AND ITS MEMBER STATES [GW]

Area/Country	Fixed, 0 to 50 m	Fixed or Floating, 50 to 100 m	Floating, 100 to 200 m	Floating, 200 to 1000 m	Total
Atlantic Arc	**510**	**585**	**974**	**585**	**2654**
Rep. of Ireland	133	299	481	316	**1230**
France	316	228	384	79	**1007**
Spain	37	18	55	103	**212**
Portugal	23	41	55	86	**205**

Technical Electricity Potential

On every 1/60° x 1/60° element of the wind speed raster file presented in Figure 2, the corresponding annual full load hours of operation (*FLH*) can be established using (Held, 2010)'s equation:

EQUATION 1

$$FLH = 728\ U - 2368 \text{ [hours per year]}$$

where U is the average wind speed.

This equation was chosen for its convenience, and for the sake of consistency with the Mediterranean Study (Konstantin Staschus et al., 2020b) for which the same relation was used.

It follows that the annual electricity production per km² can be calculated using Equation 2:

EQUATION 2

$$E_{annual} = FLH \times Capacity\ density \times Overall\ efficiency\ [\mathrm{MWh/km^2.year}]$$

where E_{annual} is the annual electricity production per km² for each 1/60° x 1/60° element, the *Capacity density* equals to 7 MW/km² as previously mentioned and the *Overall efficiency* factor equals to 0.81. The latter accounts for the resource losses due to farm effects, and for the O&M and failure downtime. This value was chosen to be consistent with the Mediterranean Study (Konstantin Staschus et al., 2020b).
The resulting technical electricity potential is presented in Figure 6. The corresponding values are given in Table 1-6.

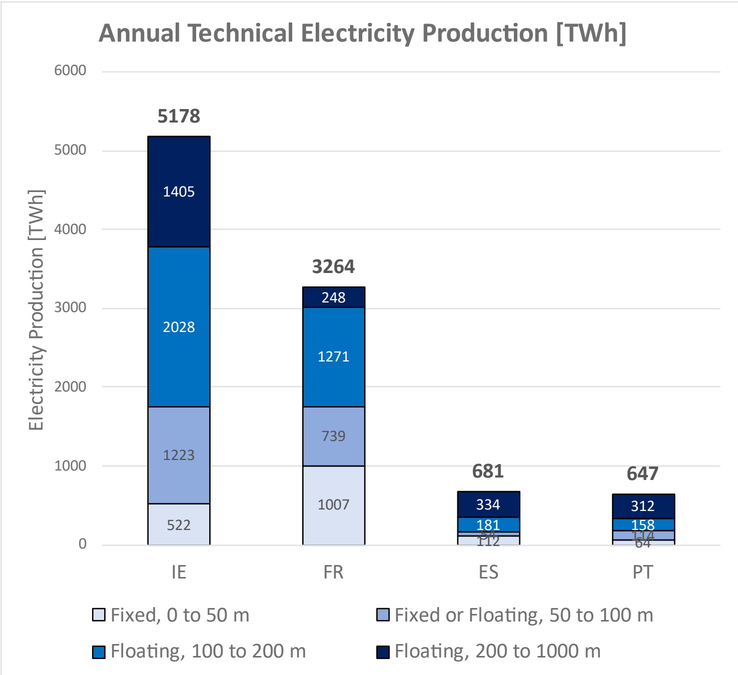

FIGURE 6 : TECHNICAL ELECTRICITY POTENTIAL FOR THE MEMBER STATES OF THE EUROPEAN ATLANTIC ARC [TWH]

TABLE 1-6 : TECHNICAL ELECTRICITY POTENTIAL FOR THE MEMBER STATES OF THE EUROPEAN ATLANTIC ARC [TWH]

Area/Country	Fixed, 0 to 50 m	Fixed or Floating, 50 to 100 m	Floating, 100 to 200 m	Floating, 200 to 1000 m	Total
Atlantic Arc	**1705**	**2131**	**3638**	**2298**	**9772**
Rep. of Ireland	522	1223	2028	1405	**5178**
France	1007	739	1271	248	**3264**
Spain	112	54	181	334	**681**
Portugal	64	114	158	312	**647**

1.2.1.3 Non-technical constraints

Non-technical constraints are also influencing the availability of offshore space for the deployment of wind farms, such as those related to the conservation of the marine environment and biodiversity, the fishing iesactivities, the oil and gas concessions, the safety of navigation and other human activities. Although these constraints do not necessarily result in strict areas of exclusion, they increase the number of barriers an ORE project is facing and are therefore less suitable for ORE deployment in the short/medium term.

The features included in the non-technical constraints are listed in Table 1-7 and further details are given in Appendix 2. Most of the georeferenced information was retrieved from the EMODnet database[30], which gives access to consistent and homogeneous European marine data at the scale of the Atlantic Arc.

TABLE 1-7 : NON-TECHNICAL CONSTRAINTS LAYERS

Features	Description	Source
Marine Protected Areas (MPA)	**CDDA** The Common Database on Designated Areas (CDDA) is the official source of marine protected areas for European countries. It includes nationally designated areas such as marine conservation zones (MCZ), marine nature parks, nature reserves, national parks and other protected sites. **Natura2000** is an ecological network of protected areas setup to ensure the survival of Europe's most valuable species and habitats. It is based upon the 1979 Birds Directive and 1992 Habitats Directive. The database consists of special protection areas and special conservation interests.	**CDDA:** EMODnet Human Activities, Environment, Nationally designated areas (CDDA)[31] **Natura2000:** EMODnet Human Activities, Environment, Natura 2000[32]
Oil and Gas	Hydrocarbon extraction active licenses	EMODnet Human Activities, Oil and Gas, Active Licences[33]
Cables	Telecommunication and power cable routes	EMODnet Human Activities, Telecommunication and power cables, Actual Routes[34]
Main Shipping Routes	Based on the main International Maritime Organization (IMO) shipping routes	EMODnet Human Activities: EMSA Route Density Map[35]
Main Fishing Areas	The datasets on fishing intensity in the EU waters were created in 2021 by the International Council for the Exploration of the Sea (ICES). Fisheries overview data concern: i) the spatial distribution of average annual fishing effort (mW fishing hours) by ecoregion and gear type.	EMODnet Human Activities, Fisheries, Fishing intensity[36]

Marine Protected Areas (MPA)

The European Commission's reports (Galparoso et al., 2022), (European Commission, 2021) and (European Commission, 2020a) address the potential effects of offshore wind deployment on different groups of EU-protected habitats and species, as well as the effects of offshore wind farms on fisheries and aquaculture.

Notably, the type of effects is related to the implementation stages of the ORE farm (construction, operation or decommissioning), and can be temporary or permanent. Some

[30] https://www.emodnet-humanactivities.eu/
[31] https://www.emodnet-humanactivities.eu/search-results.php?dataname=Nationally+Designated+Areas
[32] https://www.emodnet-humanactivities.eu/search-results.php?dataname=Natura+2000
[33] https://www.emodnet-humanactivities.eu/search-results.php?dataname=Active+Licences
[34] https://www.emodnet-humanactivities.eu/search-results.php?dataname=Telecommunication+Cables+%28actual+route+locations%29
[35] https://www.emodnet-humanactivities.eu/search-results.php?dataname=Route+density+%28source%3A+EMSA%29
[36] https://www.emodnet-humanactivities.eu/search-results.php?dataname=Fishing+Intensity

effects can be negative: during the construction phase, the marine ecosystem is temporally negatively disturbed through sediment displacement and high impulsive sounds from piling. Some other effects, such as the reef effect, can be considered as positive; the ORE devices support the development of a food chain based on the biofouling growing on their foundations. In addition, most ORE farms are '*de facto*' closed areas for fisheries and as such, can be seen as a passive refuge and recovery area resulting in higher densities and larger animals. How these modifications impact the marine ecosystem at scales larger than the ORE farm is still unclear and recommendations are made to further study the degree to which ORE development leads to modifications in biodiversity, species composition, spill-over effects and habitat characteristic (European Commission. European Climate, Infrastructure and Environment Executive Agency et al., 2021).

It results that many different views are provided by the stakeholders (often polarized by sector and areas) about how the coexistence level between MPA and ORE should be addressed, ranging from strict incompatibility (total exclusion) to ignoring MPA. These positions are largely dependent on the background of the stakeholder and its direct interactions with ORE, including collaborative opportunities with other stakeholders (European Commission, 2021).

Past experiences show that offshore wind farms have already been consented within (Fécamp[37]) or partly overlapping (Dieppe-Le Tréport[38], Baie de St-Brieuc[39]) an MPA, provided appropriate mitigation measures are adopted.

The Marine Protected Areas occupy the most significant proportion of the surface suitable for ORE deployment along the Atlantic Arc, notably in France, Spain and Portugal. In comparison, Ireland has a limited surface dedicated to MPAs, although active requests of prioritizing and developing environmental conservation prior to ORE development are made. According to (European Commission, 2022), the Green Deal objectives set 30% of land and sea to become protected areas, 1/3 of which will benefit strict protection. The resulting loss in offshore wind capacity potential is presented in Table 1-8, when considering that offshore wind can not be deployed in MPA.. Should appropriate mitigation measures be adopted and considering that some offshore wind farms have already been consented in MPAs, a certain proportion of the space allocated to MPAs may still be granted for ORE deployment. When an estimated proportion of 15% is granted, the resulting losses are presented in Table 1-9. The specific conditions required to consider co-location between ORE and MPA are presented in section 4.1.2

Oil and Gas

Areas with active oil and gas exploitation and exploration licenses were included in the set of human activities possibly competing with the deployment of ORE.

Cables

Any human activity occurring in the vicinity of underwater cables can represent a significant hazard to the cable. The Genova Convention on the Continental Shelf (Article 5) delimits a safety distance of 500 m around these installations.

Main Shipping Routes

The waters of the Atlantic Arc experience high maritime traffic intensity along navigation channels that give access to the main European harbors. High traffic shipping lanes represent a major hazard for ORE farms and will most likely not be identified as a potential

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[37] https://dieppe-le-treport.eoliennes-mer.fr/
[38] https://dieppe-le-treport.eoliennes-mer.fr/
[39] https://ailes-marines.bzh/

zone for ORE deployment. A low traffic shipping lane might be willing to accommodate an ORE farm.

Main Fishing Areas
The average number of fishing hours per year was used as a single proxy to characterize the fishing intensity at the scale of the European Atlantic Arc. A minimum threshold of 120 mW fishing hours was used to identify the main commercial fishing areas.

Military/Defense Areas
Military and defense areas along the European Atlantic Arc are an important limiting factor for the deployment of ORE. However, several aspects led not to consider these areas in the site selection process for the current section:

- Spatial information can either be unavailable for all countries or available in a format which is not suitable for the processing used in the study.
- The way how military areas can/cannot collocate with ORE remains an open question and is an action mentioned in the November 2020 Offshore renewable strategy. In September 2022, the European Commission and the European Defence Agency are due to begin a project to identify barriers for offshore renewable energy developments in areas reserved for defence activities and improve co-existence. For the selection of macroscale areas, preference was made to be representative of the planification stage and consequently to be compliant with the Maritime Spatial Planning of each country of the European Atlantic Arc (Ireland[40], France[41], Spain[42] [43] and Portugal[44]).
- Ongoing/Early planning offshore wind projects are already in progress in military designated areas.
- Early recommendations were made to use the Mediterranean Study as an example, where military designated areas are not considered.
- Some information about the spatial extent of a selection of military areas retrieved for France, Spain and Portugal is presented in Appendix 2.

Additional non-technical constraints
We reviewed possible additional non-technical layers, such as dredging/dredge spoil dumping areas, aquaculture, aggregate extraction areas, archaeology, etc. but these were not added. We expect them to have only limited influence in process of selecting macro-scale areas due to reduced extent or limited risks regarding possible conflicts of use.

The mapping of the non-technical constraints is presented in Figure 7.

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[40] https://atlas.marine.ie/
[41] Planification des espaces maritimes : carte des vocations (arcgis.com)
[42] Visor INFOMAR - MITERD, CEDEX (miteco.es)
[43] https://map.4coffshore.com/offshorewind/
[44] https://webgis.dgrm.mm.gov.pt/portal/apps/webappviewer/index.html?id=df8accb510bc4f33963d9b03bf3674b8

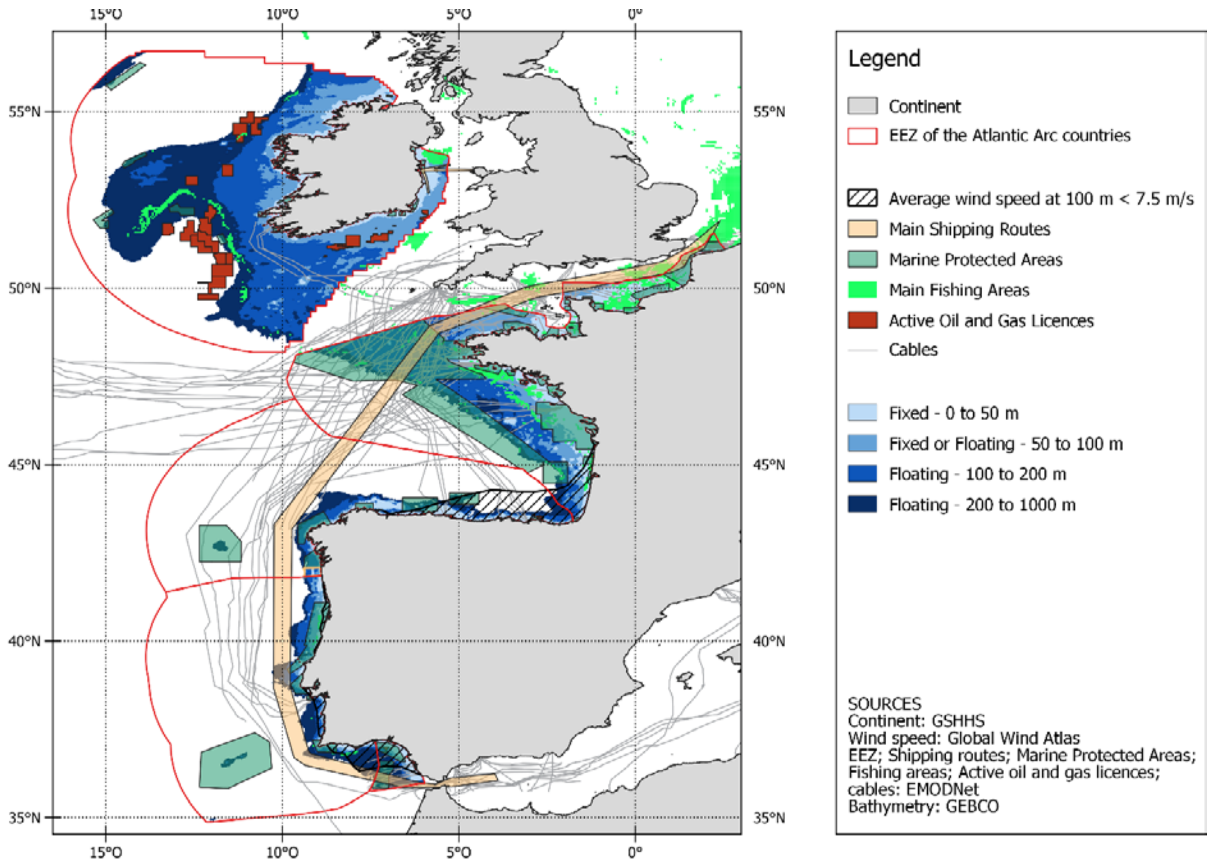

FIGURE 7 : NON-TECHNICAL CONSTRAINT LAYERS

TABLE 1-8 : LOSSES IN SURFACE AVAILABILITY/CAPACITY POTENTIAL RELATED TO STRICT INCOMPATIBILITY BETWEEN MPA AND OFFSHORE WIND FARMS

Area/Country	Fixed, 0 to 50 m	Fixed or Floating, 50 to 100 m	Floating, 100 to 200 m	Floating, 200 to 1000 m
Atlantic Arc	**34.9%**	**15.0%**	**26.7%**	**14.2%**
Rep. of Ireland	**21.7%**	**0.2%**	**0.0%**	**0.0%**
France	**49.0%**	**25.1%**	**58.9%**	**64.6%**
Spain	**7.3%**	**13.5%**	**29.7%**	**22.4%**
Portugal	**30.4%**	**55.6%**	**23.2%**	**4.9%**

TABLE 1-9 : LOSSES IN SURFACE AVAILABILITY/CAPACITY POTENTIAL WHEN 15% OF THE MPA SURFACE IS ACCEPTED FOR OFFSHORE WIND FARMS

Area/Country	Fixed, 0 to 50 m	Fixed or Floating, 50 to 100 m	Floating, 100 to 200 m	Floating, 200 to 1000 m
Atlantic Arc	**29.7%**	**12.8%**	**22.7%**	**12.1%**
Rep. of Ireland	18.4%	0.2%	0.0%	0.0%
France	41.6%	21.3%	50.1%	54.9%
Spain	6.2%	11.5%	25.2%	19.1%
Portugal	25.8%	47.3%	19.7%	4.2%

1.2.1.4 Site selection

The main purpose of this exercise is to highlight the areas compliant with the technical constraints presented in section 1.2.1.2 (depth < 1000 m, sufficient resource) and showing reduced non-technical overlapping interest as presented in section 1.2.1.3. Note that all the areas do not necessarily correspond to areas with the lowest, non-technical, ranking indexs (some of them may overlay with MPA or underwater cables). The main supporting reason is that the preference was given for the selection process to be in line with the planification stage, by encompassing the areas specifically designated as interesting/high priority zones/concept zones for the deployment of offshore wind energy by the national Maritime Spatial Planning of each country of the European Atlantic Arc (Ireland[45], France[46], Spain[47] [48] and Portugal[49]). Two additional areas were selected, without referring to the national MSP in Ireland (IRa) and France (FRa), and essentially to benchmark the economics of multi-gigawatt, far offshore wind farms, including offshore floating stations and cross-border power exchanges opportunities. The selected areas are presented in Figure 8.

Note that FR1, FR2, ES1, ES2, PTa, PT2 and PT3 areas show higher possibility of interference with military designated areas (see Appendix) although they comply with the national MSP in terms of ORE deployment priorities.

Table 1-10 gives the surface of the selected areas and Table 1-11 gives the corresponding capacity potential assuming a capacity density of 7 MW/km².

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45 https://atlas.marine.ie/

46 Planification des espaces maritimes : carte des vocations (arcgis.com)

47 Visor INFOMAR - MITERD, CEDEX (miteco.es)

48 https://map.4coffshore.com/offshorewind/

49 https://webgis.dgrm.mm.gov.pt/portal/apps/webappviewer/index.html?id=df8accb510bc4f33963d9b03bf3674b8

FIGURE 8 : SITES SUITABLE FOR OFFSHORE WIND FARM DEPLOYMENT

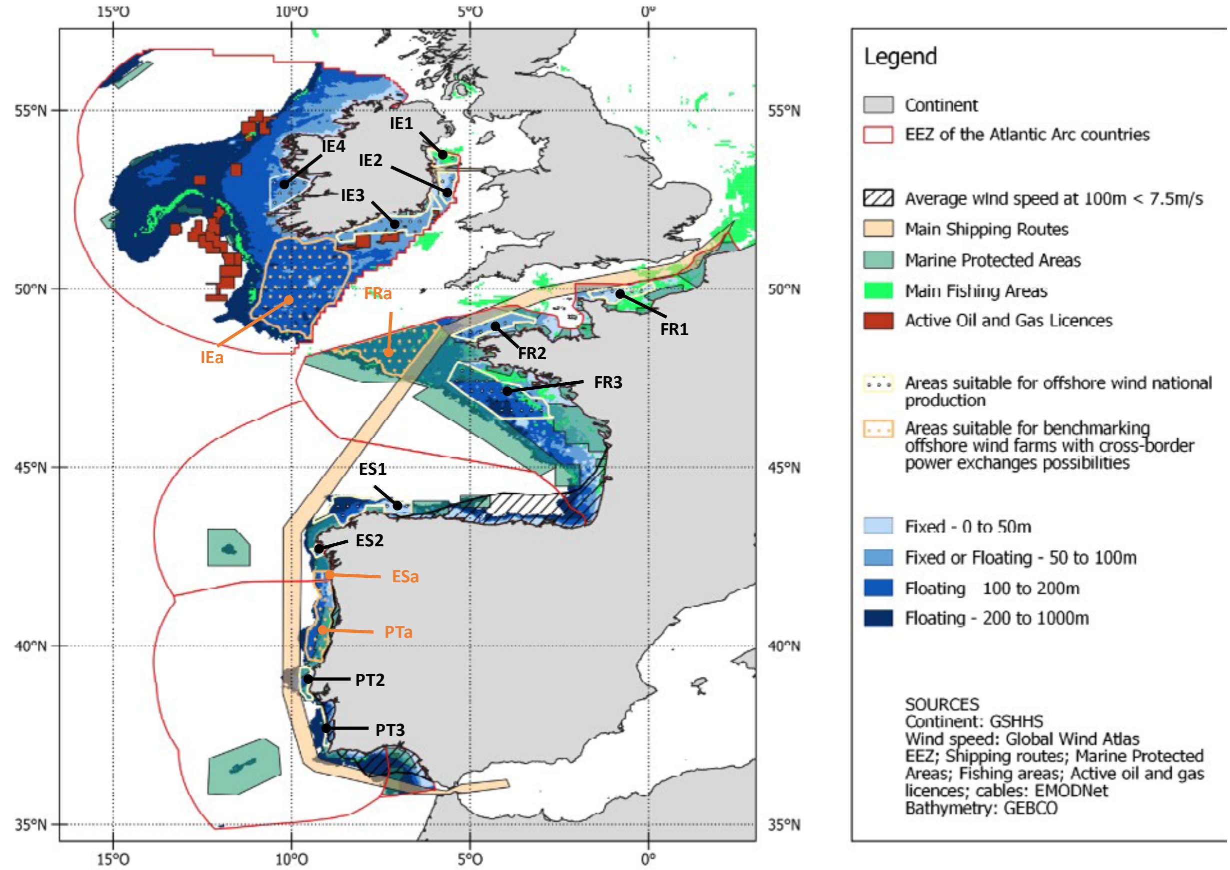

TABLE 1-10 : SURFACE OF THE SELECTED AREAS SUITABLE FOR OFFSHORE WIND DEPLOYMENT [KM²]

Area/Country	Area Name	Fixed, 0 to 50 m	Fixed or Floating, 50 to 100 m	Floating, 100 to 200 m	Floating, 200 to 1000 m	All depths considered	Total
Atlantic Arc		**9721**	**30428**	**76058**	**8823**	**125030**	**119888**
Ireland	**IE1**	728	1087	86	0	1901	**12762**
	IE2	963	1396	61	0	2419	
	IE3	1085	7331	25	0	8441	
	IE4	205	3633	1304	0	5142	
	IEa	*245*	*3153*	*35798*	*1221*	*40417*	***40417***
France	**FR1**	2864	832	0	0	3696	**27407**
	FR2	3	4475	637	0	5114	
	FR3	33	2328	13439	2796	18597	
	FRa	*33*	*301*	*15229*	*215*	*15778*	***15778***
Spain	**ES1**	1843	640	2586	3557	8626	**10411**
	ES2	169	202	402	10	784	
	ESa	*195*	*235*	*493*	*78*	*1001*	
Portugal	***PTa***	*1259*	*3774*	*4583*	*650*	*10267*	**13113**
	PT2	81	958	913	61	2012	
	PT3	15	83	501	235	834	

TABLE 1-11 : TECHNICAL CAPACITY POTENTIAL [GW] OF THE SELECTED AREAS SUITABLE FOR OFFSHORE WIND DEPLOYMENT ASSUMING A CAPACITY DENSITY OF 7 MW/KM²

Area/Country	Area Name	Fixed, 0 to 50 m	Fixed or Floating, 50 to 100 m	Floating, 100 to 200 m	Floating, 200 to 1000 m	All depths considered	Total
Atlantic Arc		**68**	**212**	**529**	**60**	**869**	
Ireland	**IE1**	5	8	1	0	13	**125**
	IE2	7	10	0	0	17	
	IE3	8	51	0	0	59	
	IE4	1	25	9	0	36	
	IEa	*2*	*22*	*251*	*9*	*283*	***283***
France	**FR1**	20	6	0	0	26	**192**
	FR2	0	31	4	0	36	
	FR3	0	16	94	20	130	
	FRa	*0*	*2*	*107*	*2*	*110*	***110***
Spain	**ES1**	13	4	18	25	60	**66**
	ES2	1	1	3	0	5	
	ESa	*1*	*2*	*3*	*1*	*7*	***7***

Portugal	***PTa***	*9*	*26*	*32*	*5*	*72*	***72***
	PT2	*1*	*7*	*6*	*0*	14	**20**
	PT3	*0*	*1*	*4*	*2*	6	

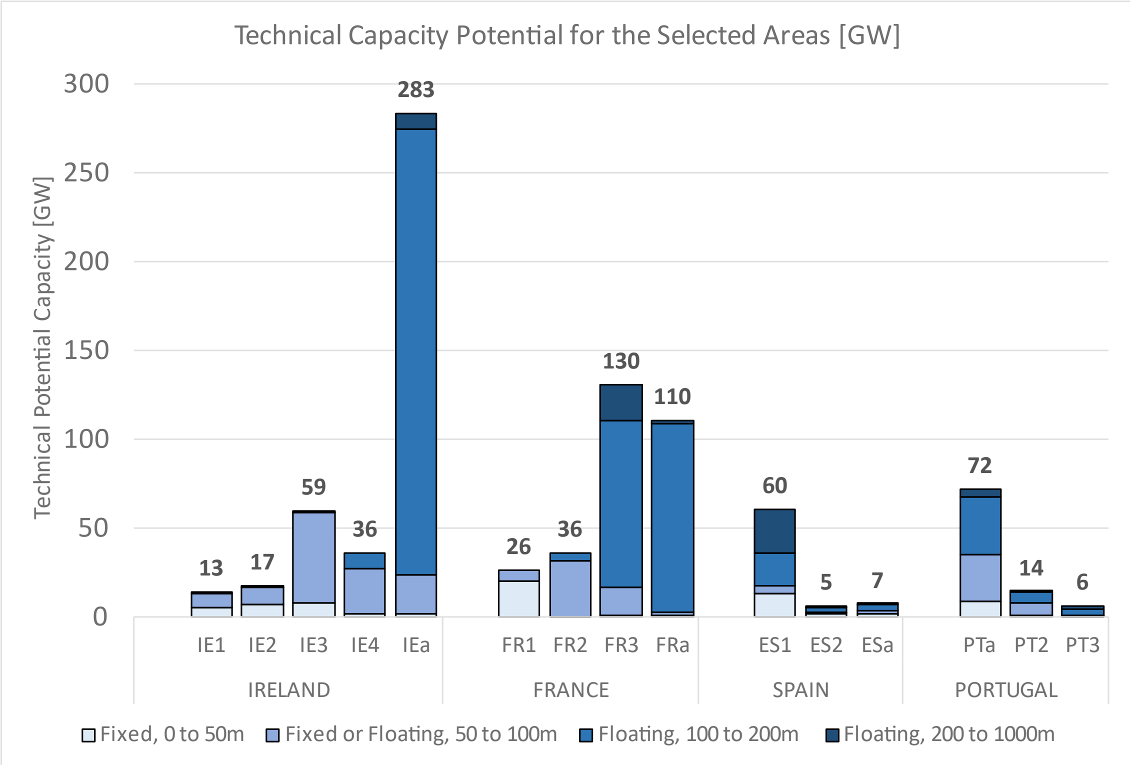

FIGURE 9 : TECHNICAL CAPACITY POTENTIAL [GW] OF THE SELECTED AREAS SUITABLE FOR OFFSHORE WIND DEPLOYMENT ASSUMING A CAPACITY DENSITY OF 7 MW/KM²

1.2.2. Wave energy

The general perspective may be apprehended from two criteria: average wave power and Wave Exploitability Index (WEI) (Figure 10 and Figure 11, respectively), the latter calculated following the definition by Martinez and Iglesias (2020):

EQUATION 3

$$WEI = \frac{\overline{H_{rms}}}{H_{max}}$$

where $\overline{H_{rms}}$ and H_{max} are the mean root-mean-square and the maximum individual wave height, respectively. Hence, the Wave Exploitability Index is the ratio of two variables representing the normal operating conditions at a certain location and the extreme conditions that the wave energy converter (WEC) must withstand. Other things equal, the greater the WEI, the greater the attractiveness of an area for wave energy exploitation.
The average wave power (Figure 10) is computed using 20 years' worth of data (2000-2019) from the IBI-MFC (Iberian Biscay Irish – Monitoring Forecasting), with an hourly temporal resolution and 0.05°x0.05° spatial resolution. The WEI (Figure 11) is computed

with 40 years' worth of data (1979-2019) from the ERA-5 database, with an hourly time resolution and 0.5°x0.5° spatial resolution.

The largest values of average wave power in the countries considered in this work (Ireland, France, Spain and Portugal) occur off the west coast of Ireland. Sheltered areas, notably the Irish Sea and English Channel, present low values.

In France, the Iroise Sea, West Brittany, must be highlighted. From there, the resource decreases gradually towards the southeast (into the Bay of Biscay) and towards the east (into the English Channel or Canal de la Manche).

The largest values in the Iberian Peninsula occur off Galicia (North-West Spain), in particular, in the region from Cape Finisterre to Cape Estaca de Bares, which encompasses the so-called Death Coast (Costa da Morte). From there, average power decreases both eastward along the Cantabrian coast (into the Bay of Biscay) and southward along the Atlantic coast and into Portugal. In the south of Portugal, Cape San Vicente marks a clear division – the coast to the east (the Algarve and Gulf of Cadiz) presents far lower values than the western façade.

The Wave Exploitability Index (Figure 11) tends to decrease from south to north, with relatively high values between Cape Raso and Cape San Vicente in Portugal, and off Cape Finisterre in Spain. The values off the Spanish Cantabrian, French and Irish coasts are lower, indicating a greater ratio between extreme and average wave conditions and, therefore, lower exploitability of the wave resource (Martinez and Iglesias, 2020).

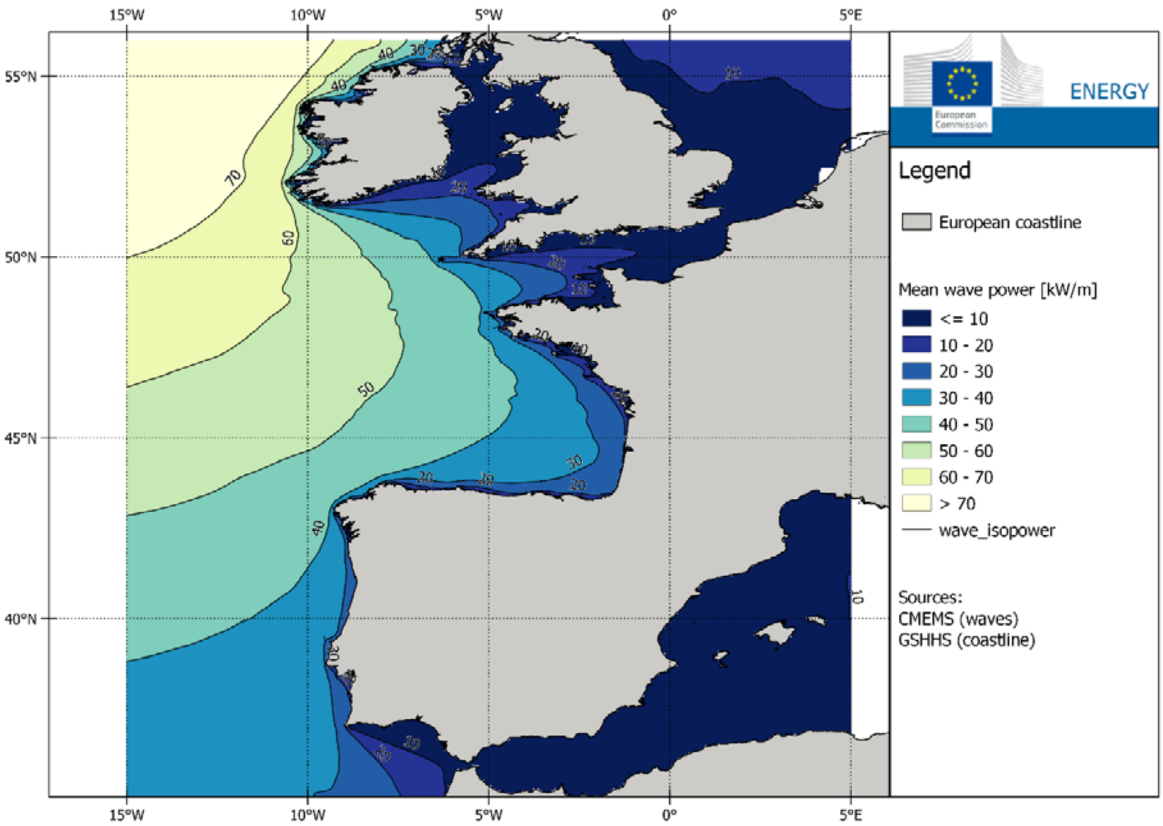

FIGURE 10 : MEAN WAVE POWER [KW/M] IN THE STUDY AREA

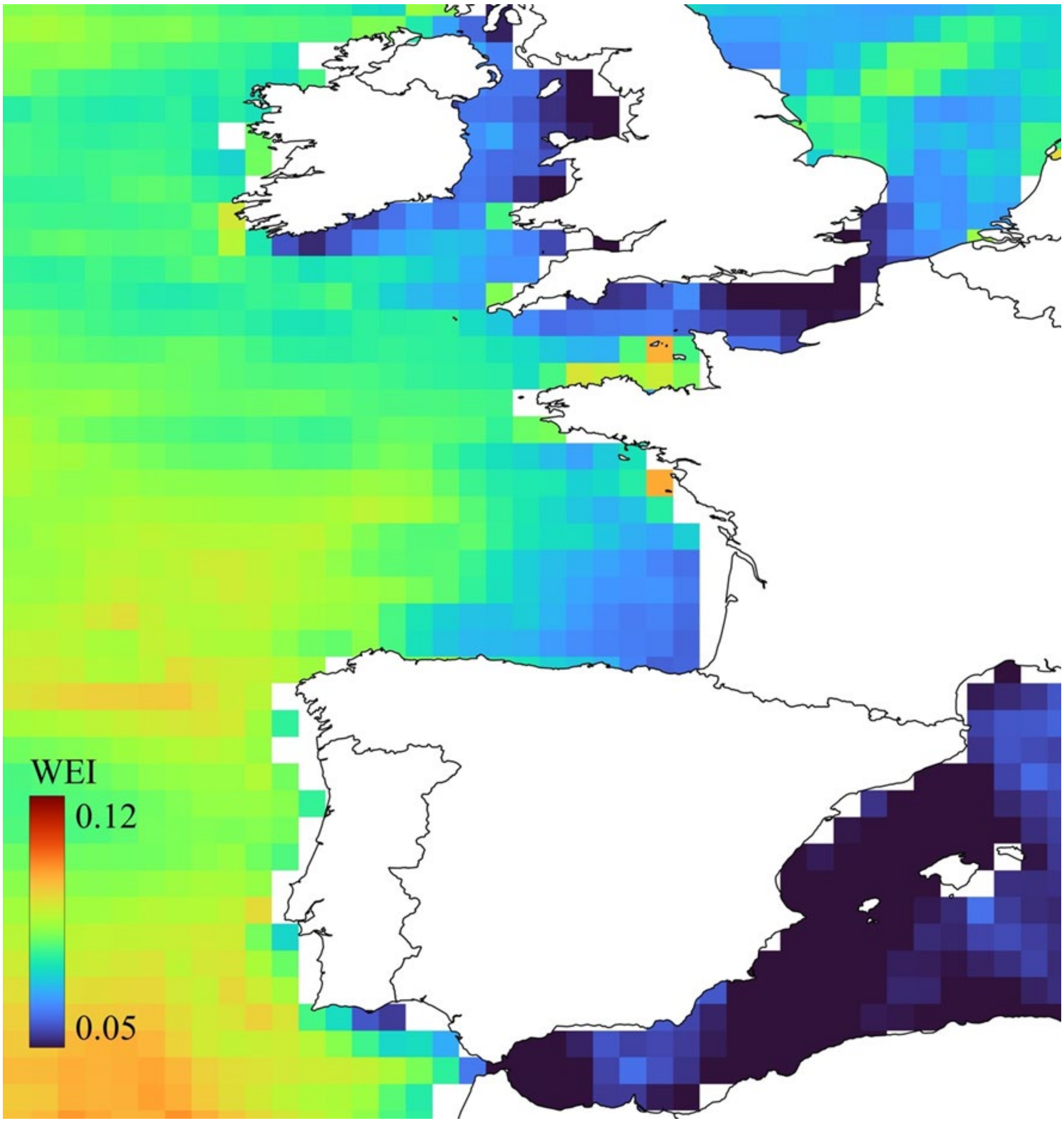

FIGURE 11 : WAVE EXPLOITABILITY INDEX IN THE STUDIES AREA (WEI, (MARTINEZ AND IGLESIAS, 2020))

A number of areas have been identified in the scientific literature as of particular interest for wave energy. These are reviewed in the following sections for each of the countries considered (Figure 12 to Figure 14), and their annual technical resource potential is calculated.

For this purpose, the methodology used in the previous Study on the offshore grid potential in the Mediterranean region (Konstantin Staschus et al., 2020a) was adopted. More specifically, taking into account the fact that the areas considered are not delimited strictly speaking in the corresponding references, the results are expressed per square kilometre.

Based on the Ocean Energy Systems/International Energy Agency LCOE report (OES & IEA, 2015), a capacity factor is estimated as follows:

EQUATION 4

$$CF = 0.0445\, P^{0.552}$$

where P is the wave power in kW/m. The annual technical resource potential for wave energy, expressed in GWh/(yr*km^2), is calculated for each area based on the full-load hours (FLH), i.e., the number of hours that the wave energy converter (WEC) would have to operate at nominal power to produce the energy output corresponding to the period considered. Following the previous Study on the offshore grid potential in the Mediterranean region (Konstantin Staschus et al., 2020b), the capacity density is assumed to be 12.5 MW/km^2, with the operational efficiency of the WECs estimated at 95% (OES & IEA, 2015).

1.2.2.1 Republic of Ireland

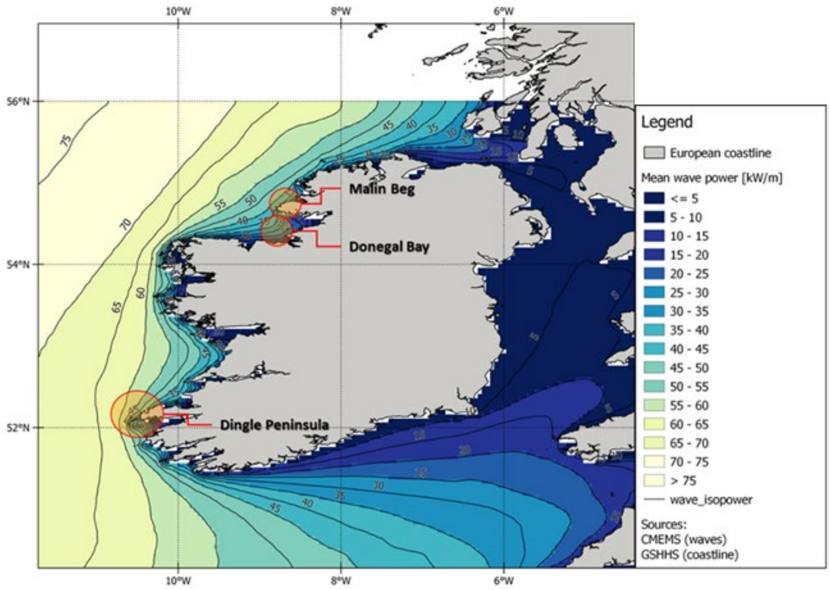

FIGURE 12 : MEAN WAVE POWER [KW/M] AND MAIN LOCATIONS FOR WAVE ENERGY PRODUCTION IN IRELAND

As mentioned before, Ireland stands out in terms of average wave power. The Northwest is the most energetic region, followed by the Southwest, with the following areas of interest covered by the literature: ***Malin Beg*** (Gaughan and Fitzgerald, 2020), ***Donegal Bay*** (Gallagher et al., 2016) and ***The Dingle Peninsula*** (Gallagher et al., 2013), see Figure 12.

1.2.2.2 France

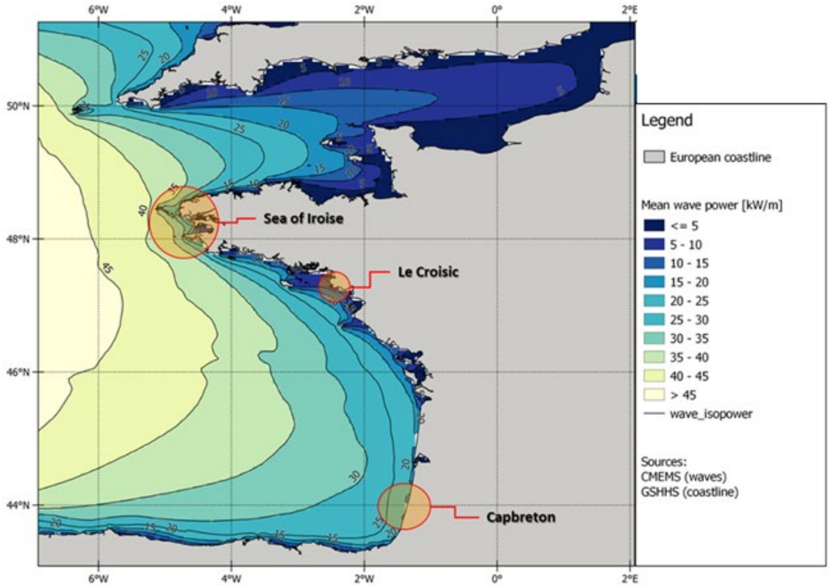

FIGURE 13 : MEAN WAVE POWER AND MAIN LOCATIONS FOR WAVE ENERGY PRODUCTION IN FRANCE

From the Iroise Sea off West Brittany, average wave power decreases eastward into the English Channel and southeastward into the Bay of Biscay. Particular areas discussed in the literature are ***Le Croisic*** (Soares et al., 2014), ***Sea of Iroise*** (Guillou, 2015) and ***Capbreton*** (Delpey et al., 2021), see Figure 13.

1.2.2.3 Spain and Portugal

The region with the largest resource is Galicia (North-West Spain) and, in particular, the coast between Cape Finisterre and Cape San Adrian – the Costa da Morte, or Death Coast, so called for the large number of shipwrecks that occurred in this highly energetic area. To the south, towards Portugal, the resource is slightly weaker but still substantial (excepting naturally inside the rias). Another noteworthy area is off Cape Estaca de Bares, also in Galicia. To the east, the resource decreases gradually along the Cantabrian Coast and into the Bay of Biscay.

In the Gulf of Cadiz, south of Portugal, the resource is far weaker due to the shelter afforded by Cape San Vicente.

Particular areas highlighted in the literature are ***Death Coast, Costa da Morte (Galicia)*** (Iglesias et al., 2009)***, Estaca de Bares (Galicia)*** (Iglesias and Carballo, 2010a)***, Cabo de Peñas (Asturias)*** (Iglesias and Carballo, 2010b) and ***Cabo de Ajo (Cantabria)*** (Iglesias and Carballo, 2010c), see Figure 14.

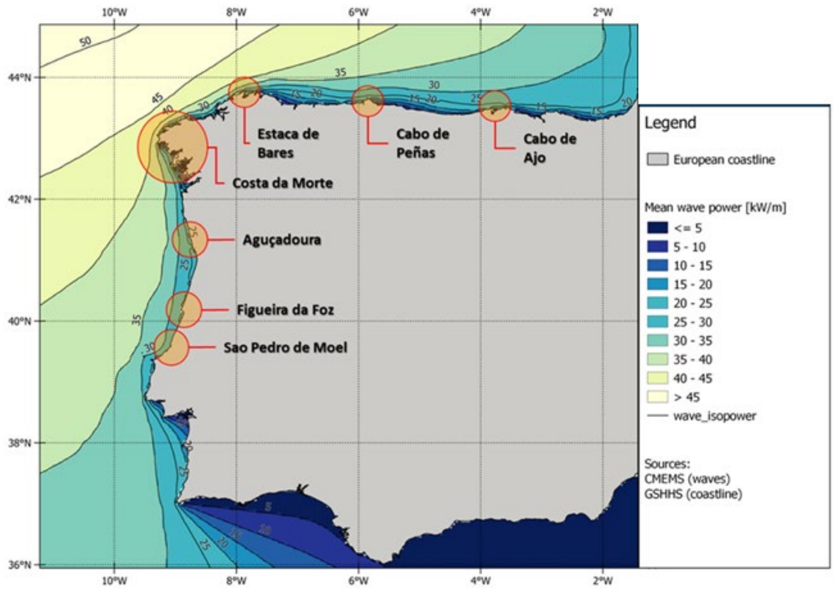

FIGURE 14 : MEAN WAVE POWER AND MAIN LOCATIONS FOR WAVE ENERGY PRODUCTION IN SPAIN AND PORTUGAL

The western Atlantic coast of Portugal presents a significant resource, with average wave power decreasing gradually from the Spanish border at the Minho Estuary to its end at Cape San Vicente. East of Cape San Vicente, i.e., in the Algarve, the resource is far weaker. Particular areas highlighted in the literature are ***Agouçadoura*** (Silva et al., 2018), ***Figueira da Foz*** (Rusu and Guedes Soares, 2009) and ***Sao Pedro de Moel*** (Mota and Pinto, 2014), see Figure 14.

1.2.2.4 Annual Wave Technical Potential for the selected areas

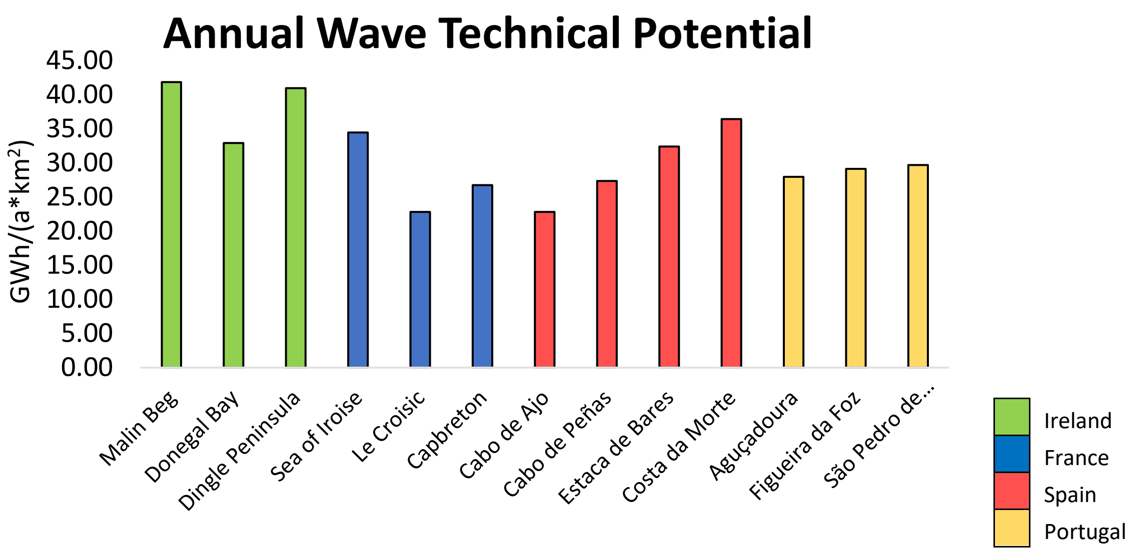

FIGURE 15 : ANNUAL WAVE TECHNICAL POTENTIAL FOR A SELECTION OF AREAS ALONG THE EUROPEAN ATLANTIC ARC

The areas highlighted in this section were selected based on their high resource level and on their appropriate WEI value. Note that a different set of technical constraints (depth limitations, minimum resource level, minimum capacity factor, etc.) may have led to a different choice of areas. However, these areas are consistent with the areas of high wave potential found in the literature.

The annual technical resource potential of each area is expressed per km^2. This approach provides an approximation to the potential of each area without the need to assume a particular surface area which, at this point, would not be justified by the existing literature or marine spatial planning. More generally, this approach enables the comparison between the different areas considered from the standpoint of the resource – the overarching objective of this section.

1.2.3. Tidal stream energy

The European Atlantic Arc experiences a semidiurnal tidal regime i.e. it is subject to two high tides and two low tides every day. The variation of the sea surface elevation drives tidal currents, which are the main determinant to assess the suitability of a site for power generation from the kinetic energy of those currents. Strong tidal currents usually require important tidal range (difference of the sea surface elevation between high tide and low tide) combined with local bathymetric/topographic constraints. In consequence, the sites where tidal current energy extraction is relevant are generally found along coastlines, inlets, channels and between headlands as in these areas, the tidal current speed is generally greater than that in the open ocean. Contrary to most sources of renewable energy, tidal energy follows a periodic signal which results in very good predictability of the tidal currents and of the corresponding power output.

In this report, the tidal energy potential assessment along the Atlantic Arc is based on the results of previous studies and on the outputs of the ATLNE2000 simulations ((Lazure and Dumas, 2008)). These simulations deliver depth-averaged tidal currents and are produced by Ifremer (French Institute for the Exploitation of the Sea) by running the MARS2D hydrodynamic model on a 2-km resolution grid and a time-step of 1h. The mean tidal current velocity resulting from the hydrodynamic model is presented in Figure 16. The areas where the average tidal current, or the peak current speed in mean spring conditions, is below 2.0 m/s are commonly considered to present insufficient resource to apply for the deployment of tidal farms ((SEAI, 2005), (O'Rourke et al., 2014), (Guillou et al., 2018)). According to direct feedbacks from tidal technology developers, the recent technological progresses made to harvest energy from slower tidal currents may lead to consider areas where the average current is at least 1.5 m/s. Those 2 thresholds (1.5 and 2.0 m/s) will be used as minimal resource limits for the present study.

The areas where the tidal currents are sufficiently strong to apply for the deployment of tidal devices are scarce and the resource requirement is, by far, the main limiting factor. According to Figure 16, the most promising sites for tidal energy are located in Ireland and France. Comparatively, Spain and Portugal show limited tidal resource.

Regarding the depth constraints, the present study considers a minimum depth of 25 m to be representative for the deployment of the tidal technologies. This value is consistent with the previous study by (Guillou et al., 2018), who have made the most comprehensive study about the tidal energy potential in English Channel and the Sea of Iroise, using a tidal current harmonic database on a 250-m grid. It is also consistent with the study from (Robins et al., 2015) about the tidal-stream energy resource over the northwest European shelf seas. A shallower depth of 15 m was suggested by tidal device developers during the Stakeholders' workshop organized in the frame of this study (Berkhout, 2022).

The capacity density of tidal farms strongly depends on the resource level, with higher current velocities being able to support higher capacity densities, and on the fitting between the resource and the technology (Horizontal Axis Turbines or Vertical Axis Turbines). According to (Ouro et al., 2022), the density ranges between about 10 MW/km² for the sites where the resource is low to intermediate, to over 100 MW/km² for the sites where the resource is higher. In the present study, an average capacity density of 45 MW/km² was used based on the average results of (Ouro et al., 2022).

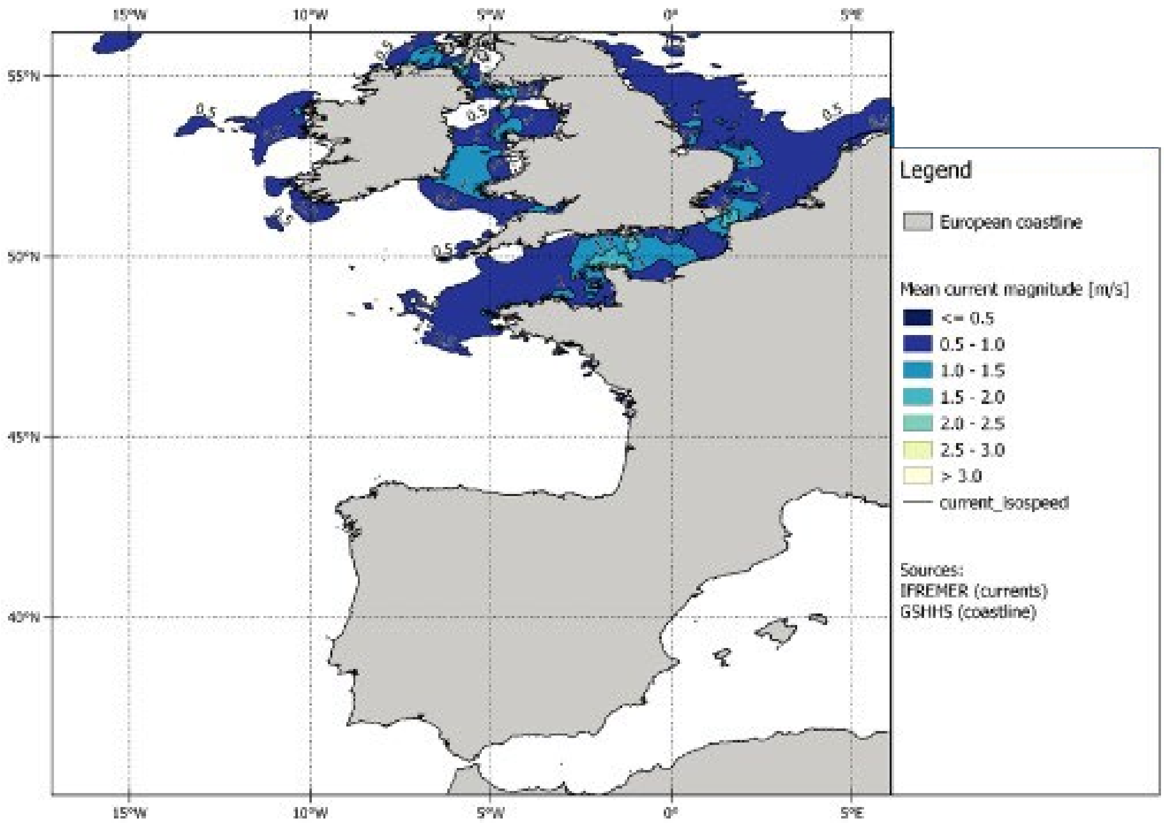

Figure 16 : Mean tidal current velocities along the Atlantic Arc

Table 1-12 : Main technical constraints used for the selection of tidal energy areas and capacity assessment

Resource (average tidal currents velocity) [m/s]	Depth [m]	Capacity density [MW/km²]
U > 1.5 m/s U > 2 m/s	*d > 25 m*	45 MW/km²

1.2.3.1 Republic of Ireland and France

When considering the technical constraints previously mentioned and presented in Table 1-12, 3 areas suitable for the deployment of tidal energy devices were selected in Ireland (Figure 17) and 4 areas were selected in France (Figure 18). The analysis did not highlight any suitable site for the deployment of tidal energy along the French Atlantic coast, in Spain or Portugal, for the chosen set of technical constraints. The main reason being reduced tidal range along these coasts (2 to 4 m) compared to that of the Irish or Celtic Seas and of the English Channel (> 4m).

The values of the surface technically available and of the corresponding capacity are shown in Table 1-. Note that these results are very sensitive to the choice of the lower threshold of the current speed and to the capacity density. The choice of the minimum current speed highly impacts the surface technically available for the deployment of tidal farms (1413 km² when choosing 1.5 m/s against 124 km² when choosing 2.0 m/s), while the capacity density modifies the electricity production potential per km² (the difference can reach a factor of 10 according to (Ouro et al., 2022)). In addition, and considering the high sensitivity of the current speed to local bathymetric/topographic features, a higher spatial resolution of the model outputs may reveal slightly different – possibly additional – areas.

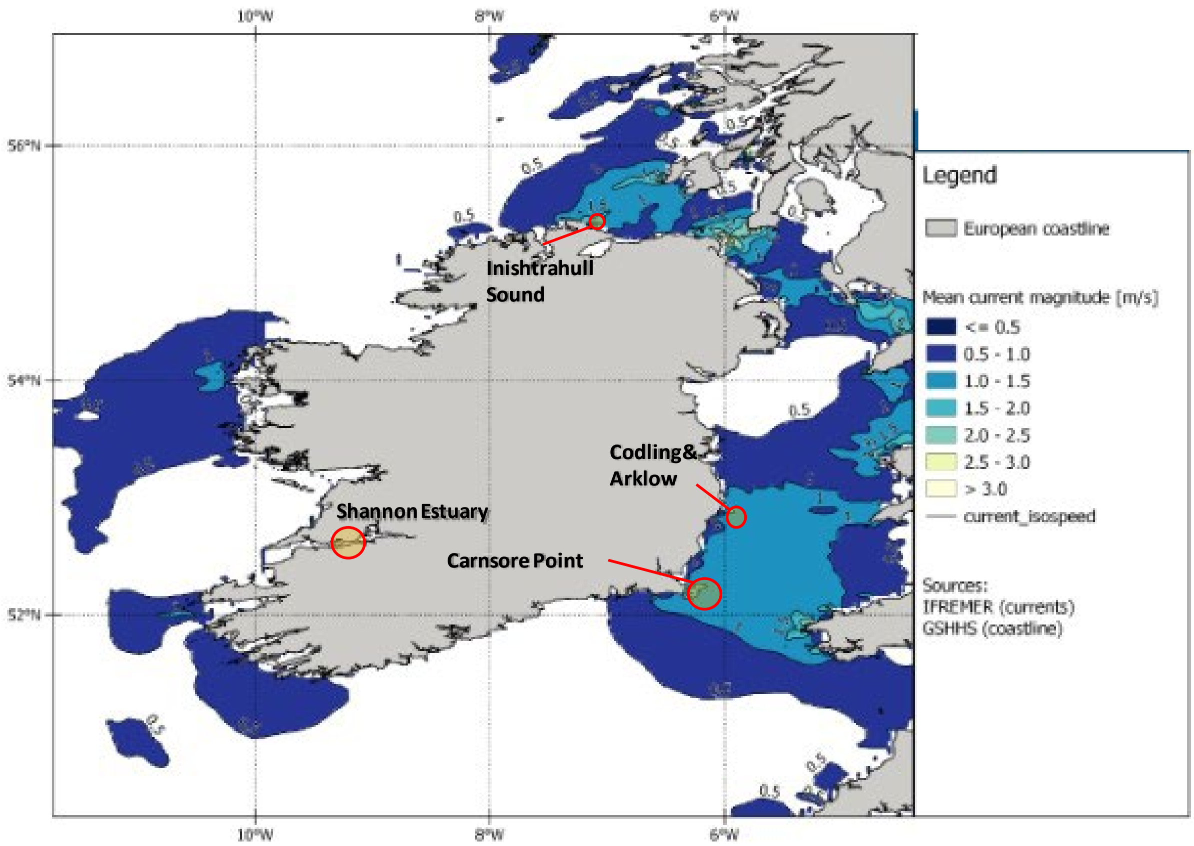

FIGURE 17 : AREAS SUITABLE FOR THE DEPLOYMENT OF TIDAL ENERGY IN IRELAND

Some studies have specifically addressed the tidal potential in the Shannon Estuary in Ireland which was not covered in the present report. Within this estuary, (Fouz et al., 2022) identify 7 sites that would be suitable for tidal energy production. However, the electric production levels in play would possibly be sufficient to partly cover the electricity consumption at local scale and the selected sites are too shallow to comply with the technical constraints used in this study.

The areas selected for France are consistent with those presented in the study by (Guillou et al., 2018) although the total surface available obtained in this study (for 1.5 m/s) represents 61 % of that obtained by (Guillou et al., 2018). Different reasons may explain this difference, the sensitivity of the results to the current velocity threshold being most likely the main factor. Finally, (Guillou et al., 2018) identify the area off the Cotentin Peninsula to be the most suitable compared to the other French areas because of low spring-neap tide variability and lower current asymmetry.

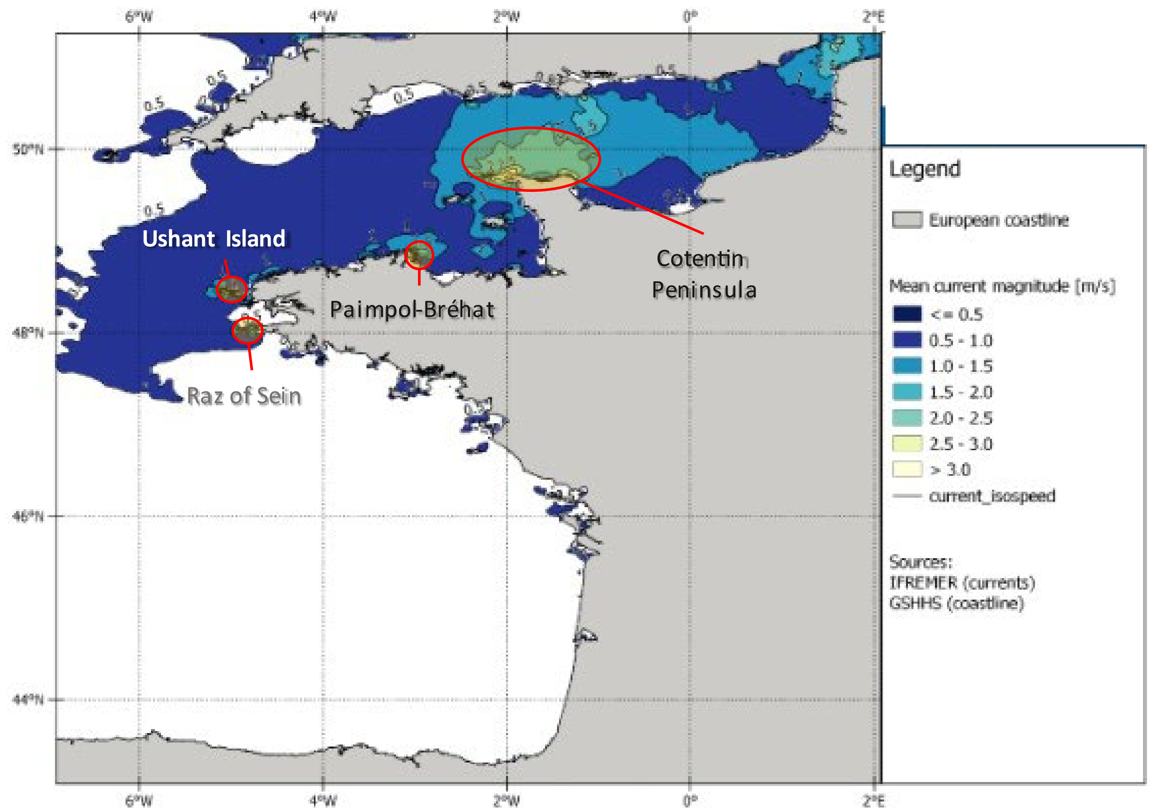

FIGURE 18 : AREAS SUITABLE FOR THE DEPLOYMENT OF TIDAL ENERGY IN FRANCE

1.2.3.2 Spain and Portugal

For Spain and Portugal, the current report did not reveal any area suitable for the deployment of tidal energy farms considering the set of technical constraints presented in Table 1-.

According to the literature, tidal energy sites in the Iberian Peninsula are essentially located in tide-driven estuaries. The studies by (Sánchez et al., 2014) and (Ramos et al., 2014) report a capacity of 1.8 MW and 400 kW in Ria de Ortigueira and Ria de Ribadeo respectively, two of the most relevant sites in Spain. From a technical point of view, the Strait of Gibraltar was also identified as a suitable area for ocean current energy by (Esteban et al., 2019). However, considering the intensity of the marine traffic and of the human activity in general in this area, the deployment of tidal farms is unlikely.

In Portugal, the tidal current resource is scarce and limited to inlets. Some tidal currents reaching 2.3 m.s^{-1} were measured and reported by (Pacheco et al., 2014) in the Ria Formosa inlet, in the frame of the assessment of tidal energy potential at this site. This area was also reported to be protected with strict environmental regulation resulting in limited probability of a tidal farm deployment.

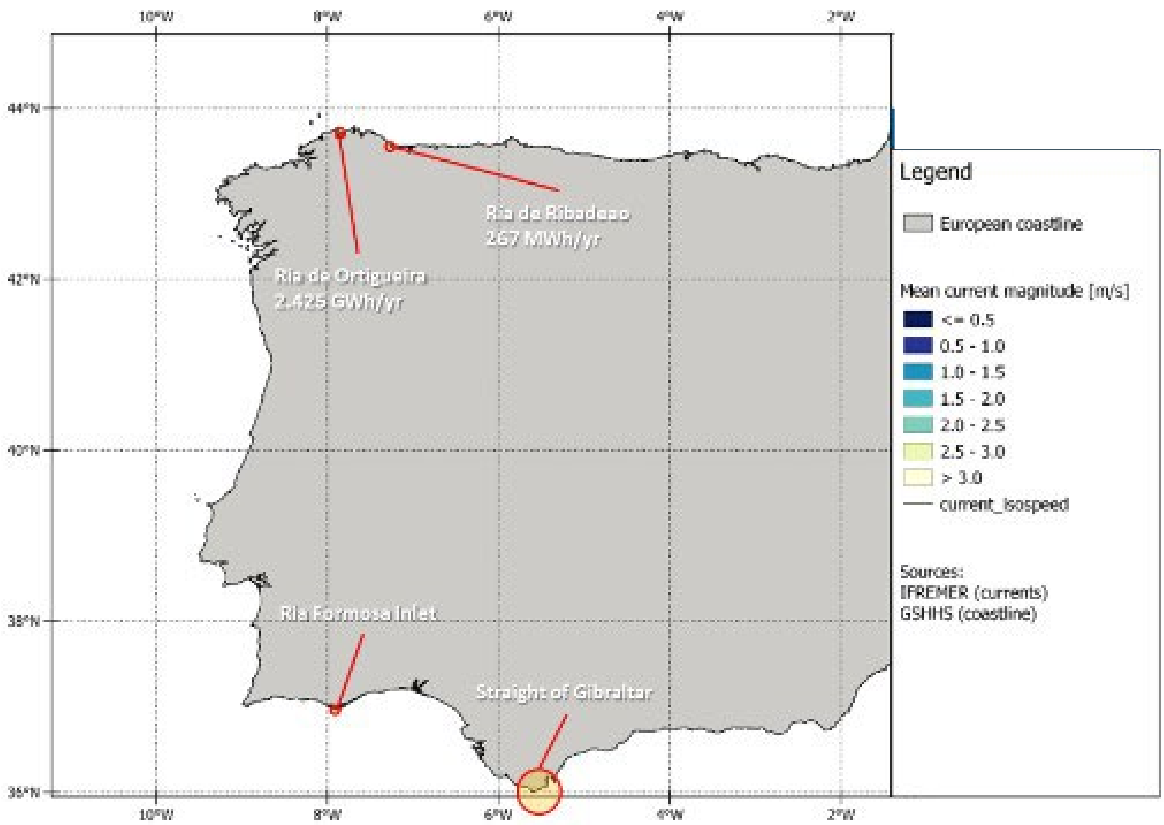

FIGURE 19 : MEAN TIDAL CURRENT MAGNITUDE IN SPAIN AND PORTUGAL WITH MAIN LOCATIONS FOR TIDAL ENERGY PRODUCTION

1.2.3.3 Technical capacity potential of the areas suitable for tidal energy deployment

The surface and corresponding technical capacity potential using a capacity density of 45 MW/km² is presented in Table 1-13 below.

1.2.4. Floating solar photovoltaics

The selection of macro-scale areas for the deployment of floating solar photovoltaics is based on the technical constraints relative to the solar resource and to depth. Resource is represented by the capacity factor (CF) and depth should be shallower than 400 m.
The capacity factor is computed as the sum over one year of the hourly output of the PV system (P_{DC}), divided by the nominal power, then multiplied by the inverter and transformer efficiency (0.95 and 0.98 respectively).

TABLE 1-13 : SURFACE [KM^2] AND CORRESPONDING TECHNICAL CAPACITY [GW] SUITABLE FOR THE DEPLOYMENT OF TIDAL ENERGY IN THE EUROPEAN ATLANTIC ARC

		Current Velocity Threshold 1.5 m/s		Current Velocity Threshold 2.0 m/s	
Area/Country	Site Name	Available Surface [km^2]	Technical Capacity Potential [GW]	Available Surface [km^2]	Technical Capacity Potential [GW]
Atlantic Arc		**1413**	**54.8**	**124**	**5.3**
Ireland	Inishtrahull Sound	23	*1.0*	0	*0.0*
	Codling & Arklow	1	*0.0*	0	*0.0*
	Carnsore Point	14	*0.6*	0	*0.0*
France	Cotentin Peninsula	1139	*51.3*	113	*5.1*
	Paimpol-Bréhat	13	*0.6*	0	*0.0*
	Ushant Island	17	*0.8*	4	*0.2*
	Raz of Sein 1	8	*0.4*	1	*0.0*
	Raz of Sein 2	2	*0.1*	0	*0.0*
Spain	Ria de Ortigueira	N/A	*0*	N/A	*0*
	Ria de Ribadeo	N/A	*0*	N/A	*0*
Portugal	Ria Formosa Inlet	N/A	*N/A*	N/A	*N/A*

The simplified model for the calculation of P_{DC} is given by the formulation below, which accounts for the electricity production sensitivity to the PV cells' temperature:

$$P_{DC}(G,T) = \frac{G}{G^r} P_p \left[1 + \mu_{Pp}\left(T - T^r\right)\right]$$

G – irradiance
Pp – peak power
μ_{Pp} – peak power temperature coefficient (given in the datasheet)
T – cell temperature

The irradiance G was retrieved from irradiance historical data from 2000 to 2021 from Copernicus ERA 5 (Hersbach et al., 2020) and the peak power coefficient was given a typical value of -0.42 %/°C. G^r and T^r are the module temperature and the irradiance at standard test condition (G^r = 1000 W/m² and T^r = 25ºC). The cell temperatures T are computed from the ambient temperature (T_{amb} downloaded from ERA 5), using the following formula:

$$T = T_{amb} + \frac{G_{800}(NOCT - 20)}{800}$$

where NOCT = 45°C is the Normal Operating Cell Temperature and G_{800} = 800 W/m².

Figure 20 shows the color-coded capacity factor, and the areas combining a depth shallower than 400 m, a minimum capacity factor of 15 % and a maximum average significant wave height of 3 m. The Atlantic part of Spain was not considered in this analysis considering the much more favourable conditions for the deployment of floating solar PV expected along the Mediterranean coast of Spain.

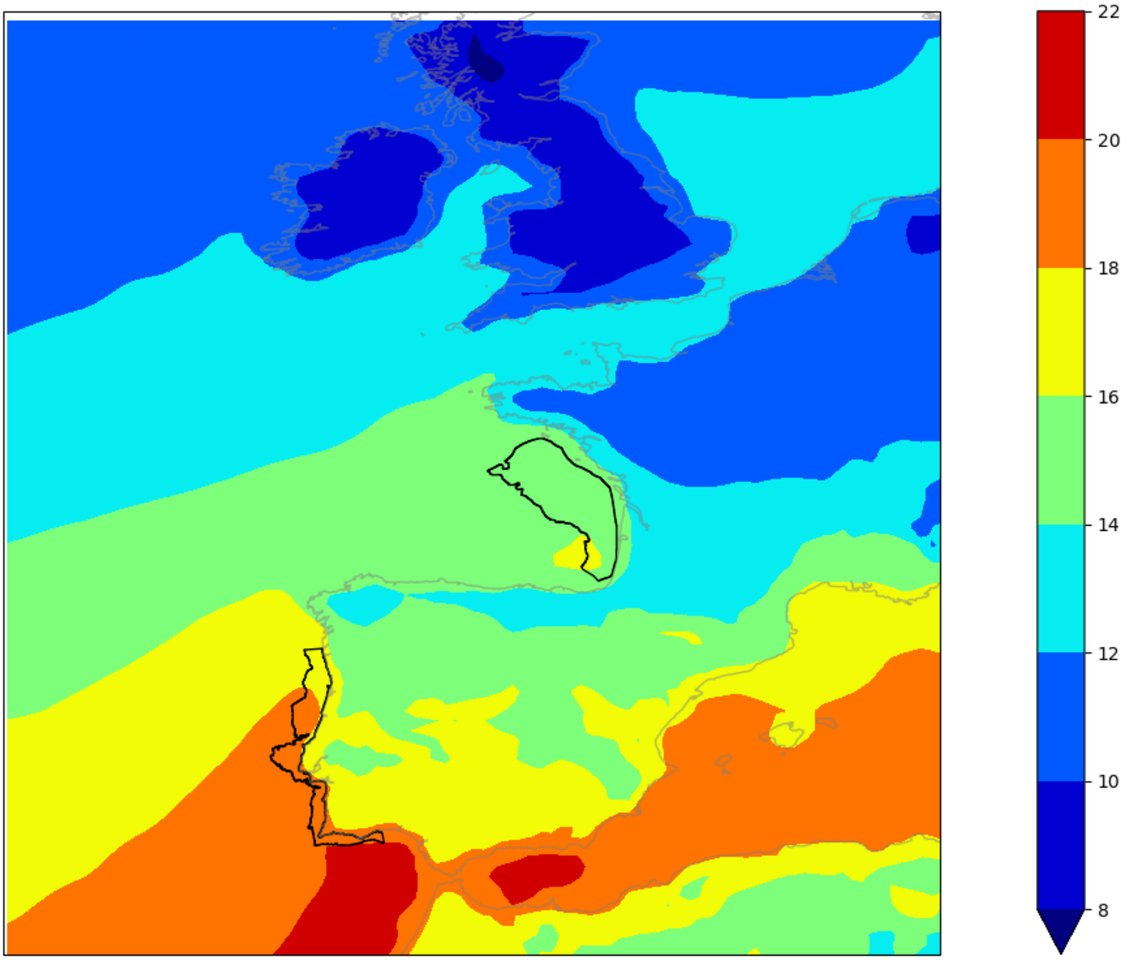

FIGURE 20 : CAPACITY FACTOR [%] AND MACRO-SCALE AREAS RESPECTING THE SET OF TECHNICAL CONSTRAINTS FOR THE FLOATING SOLAR ENERGY

1.3. Identification of ORE technical challenges in the European Atlantic Arc

There is a sudden sense of urgency in Europe for addressing the technical challenges preventing the massive deployment of offshore renewables. As the consequences of European dependence on imported fossil fuels have now, more than ever, jumped to the fore, out from distant land and distant future and onto daily horrific images at the Union's doorstep, there are high hopes that engineering prowess could accelerate offshore deployments, alleviate land-use issues for renewables, and help deliver a safer and more sustainable energy system.

What are the technical barriers to repeating and scaling up the success of offshore wind in the North Sea, this time on Europe's Atlantic seaboard? This section provides a brief overview of the main technical challenges for offshore wind, offshore solar, tidal energy and wave energy.

1.3.1. Offshore wind energy technical challenges

To impact European energy security and decision-making regarding offshore grid design, offshore wind must be deployed at the scale of tens of gigawatts. The main technical challenges to achieve this scale of deployment in the European Atlantic include:

- **Depth**: the surface available at depths less than 40 m, where current offshore wind technology is competitive, is insufficient for deployments at scales of tens of gigawatts
- **Larger monopile foundations**: currently the most common and cost-competitive foundation in offshore wind, monopiles may become competitive beyond 40 m depth if manufacturing, transport and installation of steel tubes over 10 m in diameter become practical and cost-effective. This is needed to provide sufficient rigidity to the foundation.
- **Cheaper jacket foundations** could be a good solution to depths of 60 m and possibly more. R&D challenges include reducing manufacturing costs, particularly the number and costs of tubular joints, and installation in the seabed
- **Cheaper floating solutions**, if competitive, would allow deployments at depths of 200 m or more. Challenges include reducing the cost of floaters, and developing tools and vessels to reduce weather vulnerability of **heavy lift operations** between two floating platforms.
- **Significant progress is expected in the next few years** in all these areas, and the outcome of current R&D and deployments should inform decision-making regarding offshore energy and industry in the EU Atlantic, as well as offshore grid design.

These points are detailed in the following sections.

1.3.1.1 Depth

In considering deployments at the scale necessary to supply a significant part of European energy from the Atlantic, rapidly increasing depth is perhaps the critical difference with the North Sea and the Baltic. The red and yellow areas in the map below from EMODnet are those of mean depth below 40 m, roughly those where current bottom-fixed offshore wind technology is applicable. Narrow continental shelf in the Iberian Peninsula, and steep platform in France and Ireland result in much smaller usable area (Figure 21).

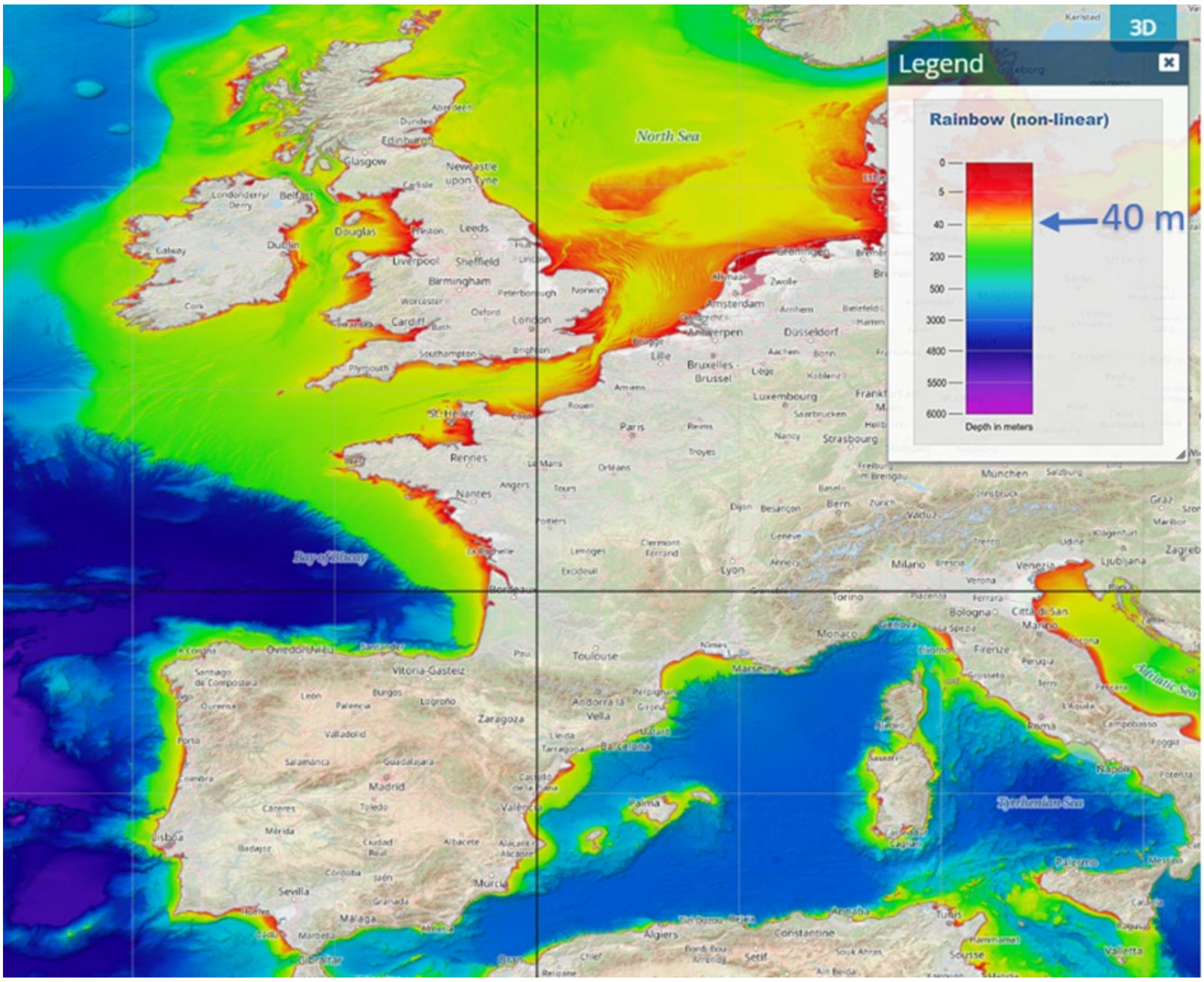

FIGURE 21 : BATHYMETRY OF WESTERN EUROPE (SOURCE: EMODNET)

However, the bathymetric chart also makes it clear that to provide a significant part of European energy needs from its Atlantic seaboard, technology suitable for deployment beyond 40 m depth is necessary. The industry is now investing considerable resources on engineering along two paths to solutions, incremental and disruptive: extending current bottom-fixed technology to progressively larger depths beyond 40 m, and floating platforms.

1.3.1.2 Extending bottom-fixed solutions to deeper sites

1.3.1.2.1 Monopile foundations

The main foundation type for bottom-fixed offshore wind is the monopile foundation. Adapting this solution to new markets has seen other challenges than just depth. For example, the construction of offshore wind farms in France, in the North of Brittany, must manage a large tidal range and currents, and a thinner sediment layer requiring driving the monopiles into hard rock. Rapid progress may be expected in these areas in the coming years. The central challenge for large deployment in the European Atlantic, however, is depth.

It was initially thought that monopiles would not be suitable for depths beyond some 20 m, but steady progress in engineering and manufacturing has made it the preferred solution for deployment as deep as 40m, and perhaps even deeper in the coming years. Ensuring sufficient rigidity, to avoid excitation of unacceptably large turbine motion by wave/wind is the central engineering challenge to extend this solution to large depths. The deeper the water, the longer the monopile, and thus the higher the lever arm exerted from the turbine thrust and wave forces. The foundation must respond with forces whose lever arm is roughly the diameter of the monopile tube, which must correspondingly increase in order to provide sufficient stiffness.

FIGURE 22 : A "BEYOND XXL" MONOPILE FOR THE YUNLIN OFFSHORE WIND FARM (IMAGE: STEELWIND NORDENHAM, FHI CORPORATION, VIA OFFSHOREWIND.BIZ)

Manufacturers have responded by delivering ever larger diameter monopiles, with so-called XXL foundations now over 10 meters in diameter and over 2000 tons of steel. Should manufacturing and installation challenges be addressed and even larger monopiles become available, they may well become a cost-competitive solution beyond 40m depth. As can be seen in the indicative cost breakdown below Figure 23), the substructure (monopile and transition piece) remains below 10% of the cost of energy, plus some of the assembly and installation costs, perhaps below 5% in most cases. Hence, some increase in foundation manufacturing and installation cost may be acceptable if compensated by larger turbine size and access to better resources at larger depths. The recently sanctioned Inch Cape wind farm offshore Scotland will use monopiles in waters as deep as 55m. Large companies are betting that monopiles will take farms to still deeper waters.

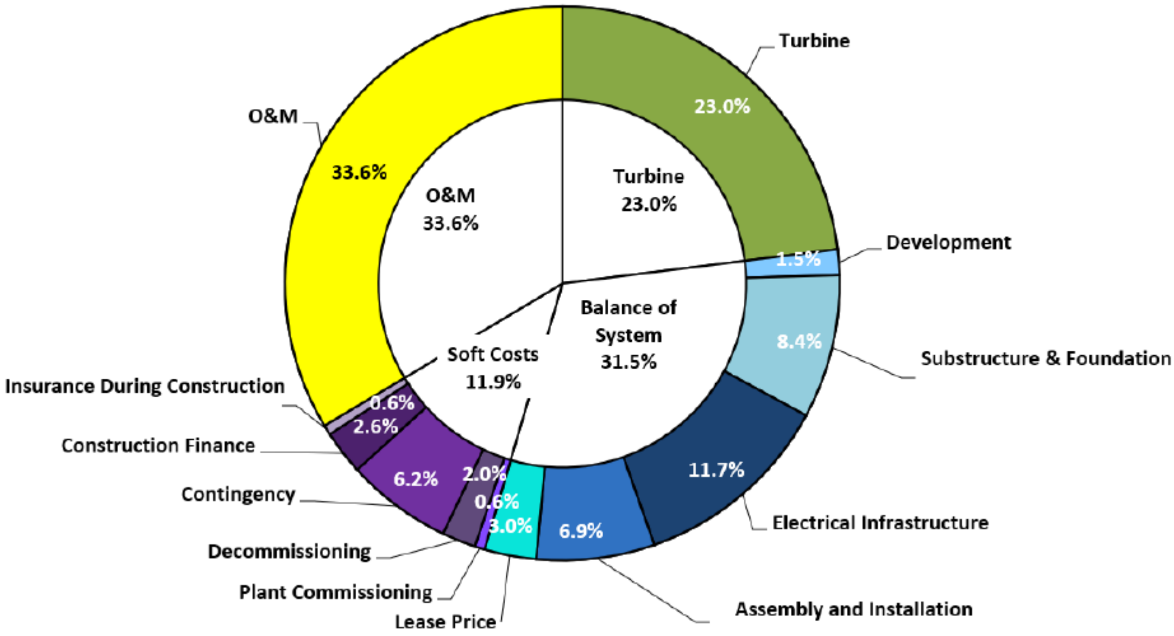

FIGURE 23 : INDICATIVE COST BREAKDOWN FOR BOTTOM-FIXED OFFSHORE WIND (FROM (STEHLY AND DUFFY, 2022))

1.3.1.2.2 Jacket foundations

The other main bottom-fixed foundation is the so-called jacket foundation. Other foundation types, such as tripods and gravity-base structure have not been selected in projects for a few years now. As truss structures, jackets can provide plenty of stiffness even at large depths. They were thus seen as the logical solution to emerge as shallow sites become rarer and farms must be built in ever larger depths. Monopiles were thought to reach engineering and manufacturing limits at some 30-40 m, and floating solutions would still be too expensive below 60m, providing a range where the market would shift to jackets. However, as industry kept on delivering ever larger diameter monopiles, jackets solutions fell in disfavour. The possibility was (and still is) contemplated that monopile solution would be chosen up to the depth were floating solutions would become competitive, bypassing jackets. However, the Seagreen Offshore wind farm, currently in construction and where jackets were chosen for a depth range of 40-60 m, may augur a comeback of jackets' market share Figure 24.

FIGURE 24 : THE SEAGREEN WIND FARM, OFFSHORE SCOTLAND, USES JACKET FOUNDATIONS IN 40-60 M DEPTH RANGE *(IMAGE: SEAGREEN WIND ENERGY)*

Much engineering for making jackets competitive at larger depth focus on reducing manufacturing costs. As truss structure, jackets are inherently more efficient in their use of steel than monopiles. The trade-off is that manufacturing complexity results in larger overall cost for the same depth. Much research has focussed on reducing the number of tubular joints and automating their manufacturing. These require cutting and welding surfaces with two different curvatures, and thus present a challenge in lowering the cost of their manufacturing while ensuring high quality. Jackets are typically fatigue-critical structures, more so than monopile, and stress concentration and thus fatigue typically occurs on these joints. Tight tolerance on these welds is thus required.
Other challenges for reducing jackets costs include transport and assembly. An important problem is that solutions and vessels highly optimised for monopiles are not always applicable. An area of focus is the anchoring in the seabed, where three or four piles must be penetrated, using a subsea hammer or vibro-hammer, or, where soil conditions permit, suction buckets. In contrast, for monopile a single pile is driven and all the complex structure, tool and handling is above the water, a much preferable situation.
In summary, it is possible that the industry will progress to where cost-competitive bottom-fixed foundations are practical in depths to 60 m and beyond. This would open perspectives for much larger deployments of bottom-fixed turbines in the European Atlantic, with important implications for European energy security and sustainability, as well as the economics of an offshore grid in the area. It is critical, thus, that decision-making in these areas be informed by the latest industry development in the coming years.

1.3.1.3 Floating wind technical challenges

When technology development makes floating wind competitive, the perspective will open for tens of gigawatts deployed in the European Atlantic. The scale of deployment would clearly impact perspectives for an offshore grid in this region. And the contribution to energy security and sustainability would be highly significant, not to mention the high job creation potential of this industry. The cost reduction in floating offshore wind technology is the single most important issue to follow regarding the possibility of a European Atlantic offshore industry and offshore grid – and possibly for the European energy future in general.

FIGURE 25 : FLOATING TURBINES ON SEMI-SUBMERSIBLE PLATFORMS *(WINDFLOAT ATLANTIC, IMAGE: EDP)*

While megawatt-scale turbines have been floated as early as 2009, with Statoil - now Equinor - Hywind demo in Norway, much of the offshore industry has remained largely on the fence until quite recently. The main reason was uncertainty regarding the capacity to bring costs down to market level. However, in the last few years there has been a rapid acceleration in investments, with many offshore industry players outlaying several hundred million euros in the technology. Commercial or pre-commercial farms in the tens of megawatts are operating or near commissioning in Scotland, France and Portugal (Figure 25). While floating wind was the bet of a few early precursors five years ago, it is now a must-have for any of the major players in offshore wind.

Nonetheless, cost remains the central concern for floating wind. Hywind Scotland, the first commercial floating wind farm, cost Equinor some 7 euros per watt (€/W) in capital expenditure (for a 30 MW farm). While this is a major cost reduction compared to the 2009 Hywind demo, this is still some three times higher than for bottom-fixed onshore wind. While no official figures are released for the floating farms now in construction, available information suggest capital expenditures still at or above 6 €/W. Much of these costs come from transport and installation, not yet optimized as in bottom-fixed farm, and are expected to come down rapidly with the scale of deployments.

However, a look at indicative, expected cost breakdowns for floating wind projects in large deployments, such as the estimates in the Figure 26 below, and comparison with bottom-fixed projects (see previous section), shows that there is a major issue with the cost of the floater. Turbine costs are similar between bottom-fixed and floating wind. But the substructure and foundation cost in bottom-fixed wind, at some 8.5% of the levelised cost of energy, is about a third of the cost of the turbine, whereas in floating wind, at above 27%, it is at least 50% higher than the cost of the turbine.

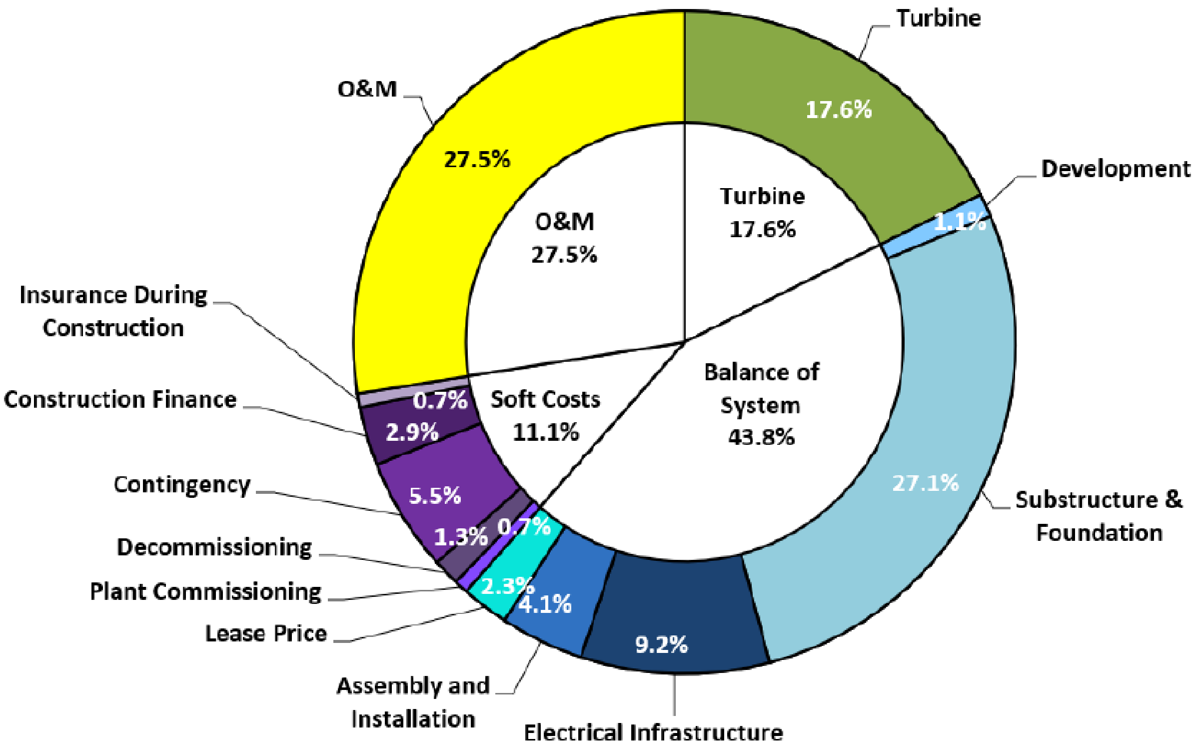

FIGURE 26 : INDICATIVE COST BREAKDOWN FOR FLOATING OFFSHORE WIND OFFSHORE WIND IN LARGE DEPLOYMENTS FROM (STEHLY AND DUFFY, 2022)

1.3.1.3.1 Heavy lift between floating bodies

Another major concern for floating wind costs concerns assembly and heavy maintenance operations. For bottom-fixed platforms, these operations are mostly carried-out from jack-up vessels, and hence from fixed platform to fixed platform. For floating wind, these operations will be carried-out from floating vessel to floating foundation. Consequently, wave-excited motions for both platforms increase dramatically. These operations often involve the heavy lift of turbine components to hundred meter high or more, with a typical tolerance to motion of some 5 cm in the final phases of the lift. The result is that wave conditions restrict lifting operations between floating platforms to few, near-waveless summer days.

Wave vulnerability of floater-to-floater heavy lift implies that with current technology, it will not be possible to ensure installation and maintenance of large scale deployments. Special vessels must be built, but these need to operate at least several months a year in order to deliver reasonable costs. This is another critical technical roadblock to the deployment of floating wind at the scale of tens of gigawatts. A good summary of these and other technical challenges for floating wind can be found in, for example, the United Kingdom's Carbon Trust-led Joint Industry Project (Carbon Trust, 2021).

FIGURE 27 : HYWIND SCOTLAND TURBINES ARE INSTALLED ON SPARS (IMAGE: EQUINOR AND WIND EUROPE)

How likely is it that these challenges will be overcome in the coming years? The offshore industry is investing several hundred million euros so that floating wind's learning rate will follow those of bottom-fixed technology. After some twenty to twenty-five years of progressive learning, bottom-fixed offshore wind costs have seen a dramatic reduction in 2016, as truly competitive auctions were introduced in the Netherlands and then Germany and the United Kingdom. This was after the industry, supported by feed-in-tariffs for over fifteen years, was able to considerably reduce uncertainties in the cost of offshore operations. Costs of offshore assembly and maintenance for floating turbines may come down quickly, as industry invents new tools and methods and invests in purpose-built vessels and special cranes.

1.3.1.3.2 Reducing floater costs

The central question is whether platform cost will similarly come down with deployments. For bottom-fixed offshore wind, costs of already highly mature components such as turbines themselves did not decrease (on a per watt basis). However, by delivering larger turbines requiring less components and operation per watt, and longer blades accessing better wind resource higher up, turbine manufacturers are playing a central part in the ongoing reduction in costs. There are expectations that this will happen in floating wind, as platform cost increases less with turbine size than power production does. However, even in ongoing projects with turbines over 10 MW, platform costs appear to remain well above turbine costs.

FIGURE 28 : MAINTENANCE BOAT AT THE IDEOL FLOATGEN BARGE AND TURBINE (IMAGE: IDEOL BW)

The industry must thus pursue floater costs reduction in other ways than simply waiting for turbine makers to deliver 20 MW or larger turbines. It is not clear yet where further cost reduction may come from for existing platform types. Their basic dimensions and weight are unlikely to significantly come down. This has been the central concern since the beginning for floating wind engineers, but stability requirements and aero-hydrodynamics may not leave much room for improvement for self-stabilised platforms – that is, platforms that use water displacement and gravity for stabilisation.

It is possible that a mooring-stabilised system could reduce platform dimensions, at the cost of important mooring and anchoring challenges. In the offshore oil and gas, such mooring-stabilised platforms have become a highly competitive solution once technology for pile anchors installation and tension legs became mature. In offshore wind, this option has seen much less investment thus far than self-stabilised platforms, but this may change in the coming years as well, especially if costs for self-stabilised platforms prove difficult to reduce as needed. Several companies are developing such solutions.

The types of platforms and their stabilisation mechanisms are in Figure 29 below. The challenge for floating wind platforms is essentially to compensate the overturning moment from the turbine thrust, either with water displacement or mooring tension. Barges such as that of Ideol BW (not shown) use hydrostatic rigidity like semi-submersible platforms, but with less concentration of the water displacement at the edge, thus reducing the buoyancy forces lever arm, but allowing, among other things, reduction in overall dimensions and manufacturing complexity.

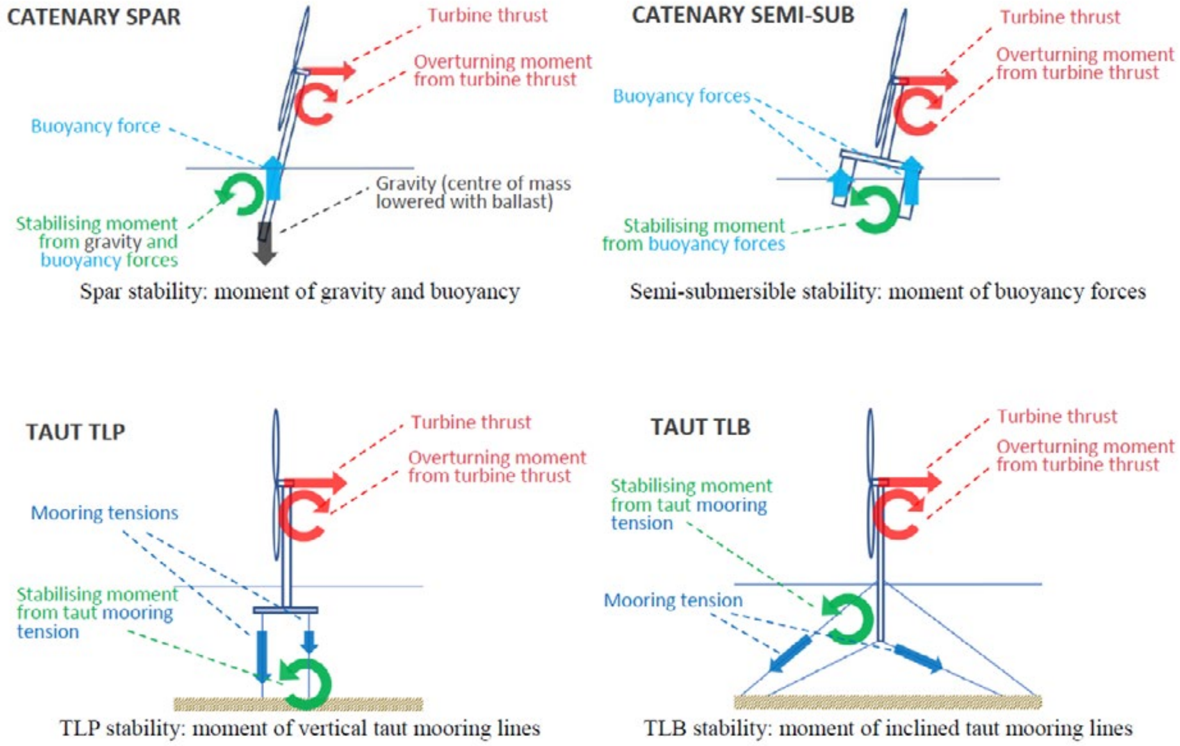

FIGURE 29 : FOUR STABILISATION MECHANISMS FOR FLOATING WIND PLATFORMS, FROM CLOCKWISE FROM TOP LEFT: SPAR, SEMI-SUBMERSIBLE, TENSION-LEG PLATFORM AND TENSION-LEG BUOY

The other possibility is that manufacturing progress would reduce cost per weight. For the moment, it remains near the range of offshore and oil and gas platforms. Steel floaters, for example, cost several euros per kilogramme of steel. In contrast, turbine towers cost in the range of 1-1.2€/kg of steel (asymptoting near cost of plates out of the steel mill). Offshore wind monopiles are also being produced ever more efficiently, with much of the welding now automated. Steel floaters may approach this range as they become standardized, manufacturing progresses to more serial and automated processes, and they become commodities rather than one-off, site-specific projects.

Concrete platforms are another pathway currently explored by several developers. Concrete typically results in heavier platforms, with steel reinforcement bars typically alone weighing almost as much as a steel platform of similar performance. However, rebars steel cost little more than steel from the mill. And unlike steel plates, concrete can be cast in complex shapes as needed for platform performance. Another important advantage is that much of the supply chain and labour can be locally sourced with concrete, and generally raw material cost is less volatile than for iron ore. The coming years will yield crucial insight in the potential for cost reduction in either steel or concrete platforms.

In summary, floating wind still face significant technical challenges for bringing down costs to market competitiveness. However, the rapid acceleration of industry investment in the last few years may deliver highly hoped for cost reduction. As is the case for bottom-fixed technology, staying up to date on technology innovation, engineering and manufacturing advances in the coming years will be crucial for decision-making to assess whether the European Atlantic will truly see tens of gigawatts of offshore wind deployed, which in turn will greatly impact the economics of an offshore grid in this area.

1.3.2. Tidal currents energy technical challenges

With wide shallow shelf seas and a coastline with many straits and inlets, the northern part of the European Atlantic is ideally configured to concentrate tidal energy. It is endowed with one of the world's best tidal resource. With regards to the design of offshore transmission infrastructure, the following are important considerations:

- The resource in the European Atlantic is concentrated in very specific areas near Brittany and around the British Isles
- Tidal barrage is a mature and competitive technology but concerns over their ecosystem impacts make it unlikely that they will be built to a scale of interest to offshore transmission infrastructure
- There are good prospects for free standing tidal turbines (tidal stream technology) to become nearly competitive within a decade, but there are uncertainties on the ecosystem impacts of deployment at scales beyond a few hundred megawatts.

FIGURE 30 : TIDE MILL OF THE ÎLE-D'ARZ, BUILT IN 16TH CENTURY (IMAGE CREDIT: WIKIMEDIA COMMONS)

For centuries, coastal villagers in the region have been harvesting this resource by building weirs for tide mills. But it is only in 1966 that Électricité de France (EDF) inaugurated the world's first tidal power station, the 240 MW Usine Marémotrice de la Rance. This technology is essentially a large tide mill, where the grain mill is replaced with bulb hydro-turbines. The first of its kind, it has by all accounts been a resounding engineering success. Electricity production is highly predictable, with a reasonably high load factor of some 25%. Costs are in the range of those of large hydropower dams – that is, the cheapest in the industry. From an engineering and power production perspective, tidal energy has thus been a technologically mature and competitive industry for several decades.

FIGURE 31 : THE 240 MW RANCE TIDAL POWER STATION, INAUGURATED IN 1966 (IMAGE CREDIT: WIKIMEDIA COMMONS)

Unfortunately, the ecosystem impacts of the Rance's 750 m long barrage have predictably been profound, especially upstream of the barrage. EDF subsequently modified the plant's operation to help regain some intertidal areas in the estuary. Many important species also benefitted from the new ecological equilibrium. Still, tidal flats are exceptionally rich ecosystems, and critical for many species. Alteration to these precious ecosystems have been a major concern, and no new construction of this scale has been undertaken for a long time.

In 2011, however, the Korea Water Resources Corporation (K-water) completed the construction of the Sihwa Lake tidal power station. It was the first project of such scale since the Rance station. With a capacity of 254 MW, it is now the largest tidal power station in the world. An interesting aspect of this project is that it has a philosophy of maximising positive environmental impacts, rather than minimising negative ones. The Sihwa lake has long been too contaminated to have any use for agriculture. The turbines were installed in an existing seawall, and power is only generated during tidal inflow. This clearly reduces power production, but the asymmetry allows for greater ventilation of the lake than was possible with the simple opening of sluice gate before the turbines were installed. A common situation in coastal areas with tidal circulation is that contaminants circle around in closed loops called tidal ellipses, greatly reducing their dispersal. The Lake Sihwa power station breaks these closed loops with the asymmetry introduced by the barrage's power production strategy. The enhanced lake ventilation is to accelerate the restoration of a healthy ecosystem and early results look promising.

Another approach to avoid negative ecosystem impacts of tidal power generation is that of free standing tidal turbines, also referred to as tidal stream generators or tidal energy converters. The technology is less mature than tidal barrage. As of May 2020 a total capacity of nearly 30 MW had been deployed, with about a third still in operation. This is quite small compared to over 500 MW of tidal barrage. Nonetheless, tidal stream technology is an active field of research and development. Most deployed devices have opted for horizontal axis turbines, but some very innovative designs are also being pursued, such as Minesto's Power Kite. Many experts and investors see good prospects for tidal stream technology to mature into a relatively competitive technology within a decade, with the capacity to grow into an important industry that creates many new jobs in coastal areas.

It is not clear, however, whether tidal stream devices can be deployed at a scale where it must be accounted for in offshore transmission infrastructure design (in the range of several gigawatts or more). The exploitable tidal resource is concentrated in a few areas, as seen in the previous section. In addition, ecosystem impacts when deployed at scales of hundreds of megawatt and beyond may be significant. Tidal flows play a critical role in many ecosystems, such as hydro-sedimentary balance, contaminant dispersal, sporophyte and gametes circulation, etc. So changes to the intensity and the geographic location of their dissipation may be expected to greatly alter important ecological processes.

1.3.3. Floating solar photovoltaics technical challenges

Offshore solar for energy production is a nascent technology, with less than a megawatt (MW) in operation worldwide. In considering potential impacts on offshore transmission infrastructure design, the following are important consideration:

- Large resource: a generation potential several times higher than that of offshore wind
- Possibly rapid development: onshore floating solar technology has gone from pilot to commercial in just a decade, which augurs well for progress offshore
- Should cost become competitive, ecosystem impacts and competition for marine space will determine the scale of deployments

Regarding its generation potential, offshore solar photovoltaic has an average areal power production is of the same order as inland. At current conversion rates, this is around ten or tens of watts per meter square (yearly average), depending on farm design. This is several times that of a wind farm. The potential to alleviate land-use requirements for renewables is thus highly significant. Should the technology be developed to where it can compete with little or no subsidy, large deployments could happen rapidly.

In about a decade, floating solar on inland water bodies has gone from pilot farms to a gigawatt-scale, mostly subsidy-free market. This remarkable progress has been achieved with relatively little government-supported research, and largely driven by private sector investment. To be clear, government support such as feed-in tariff for early farms and SME support has been essential. Nonetheless, no research program of the scale seen for, say, floating offshore wind, has been necessary for this new sector to achieve cost parity. That this success took many by surprise, and was too rapid for public funding streams to play a significant role in its R&D, is one more reason for decision-makers to closely follow the development of offshore solar technology.

As expected, the technical challenges for floating solar centre around those aspects that are absent from onshore solar, essentially floater and station-keeping (mooring and anchors). Adapting some of the power equipment, such as inverters, and the transmission infrastructure to the aquatic and moving environment, is also requiring some development.

When taking the technology from inland water bodies to offshore, designing for much larger waves is the central challenge. Dynamic loads of an amplitude and frequency much different than that for inland water may require significantly different design. In fact, those few offshore prototypes and pilots in the water have opted for completely different design philosophies than that of commercial farms in inland water bodies. One key difference is the abandonment of the modular approach (one floater per panel) that has been highly successful onshore, but it presents additional challenges offshore, such as stress concentration and resulting fatigue at mechanical connections between floaters, and delivers less installation benefits, since offshore, a relatively large boat must be used anyway. Other challenges include corrosion protection requirements and reducing costs of offshore installation and maintenance.

FIGURE 32 : 17 MW FLOATING SOLAR FARM IN PIOLENC (AKUO ENERGY)

Several companies and many experts believe that the technical challenges for offshore solar can be successfully addressed and costs can become competitive. If they are right, the main impediments to large offshore solar deployment will be the competition for marine space and ecosystem considerations.

Concerning ecosystem impacts, a rapid look at the 100 kW demonstrator shown below may be sufficient to see that the technology's footprint is much more problematic than that of offshore wind. A 10 MW turbine only occupies a water surface of the order of 10 m diameter. This 100 kW solar farm already covers over ten times as much water surface. Under this surface, shading of sunlight means primary productivity is essentially halted. This is especially undesirable in coastal seas, which are among the most productive marine ecosystems. In addition, gas exchange is halted or drastically reduced, including that of oxygen, which, at large scales, would become problematic for animal species. Oxygen content is often a key indicator aquatic of ecosystem health, and in areas affected by agricultural runoffs, it can become severely depleted due to the oxygen demand of decomposing abnormal algal blooms triggered by chemical fertilisers.

These ecosystem impacts may be significantly reduced with better designs. Shading can be reduced and/or used for ecosystem management (many species of fish like to gather under shade). Gas exchange impact also can be reduced or even reversed. Inland, mechanical oxygenation is a common aquatic ecosystem management or restoration tool, and a floating solar farm can greatly reduce costs by providing a power source just where it is needed. Some suppliers of floating solar systems are starting to integrate water-oxygenation technology in their offer. Another example of potential positive impact which should be explored, is that of synergies with floating islands which are used in lake ecosystems to provide safe resting ground, or nesting ground, to various target bird species. Floating platforms may also provide a good substrate for filter feeders (bivalve and oysters) which have been shown to play a powerful role in maintaining water quality in semi-enclosed seas.

Should technical, cost and ecosystem challenges successfully be addressed, competition for marine space will become the most important determinant of the scale of offshore solar deployments. Demand for offshore space is usually predicted to increase in the coming decades. Much of this increase, however, is to be driven by offshore wind. In this case it is likely that a practical solution will be the colocation of offshore solar farms with offshore wind farm. Shading from turbines only negligibly impacts solar production, and solar farms can be configured to not significantly impact marine operations for wind turbine maintenance. Deploying panels on a third to a half of a wind farm area can double the site's power production. Obvious cost-savings are possible in terms of transmission infrastructure. And solar production tends to be highest when wind production is lowest, reducing intermittence in production and making more efficient use of transmission assets. As such, dual-use wind/solar offshore farms may become a particularly attractive option.

FIGURE 33 : OCEAN SUN'S 100 KW DEMONSTRATOR IN KYRHOLMEN (IMAGE: OCEAN SUN)

2. PRODUCTION SCENARIOS

2.1. Offshore Renewable Energy potential market

Offshore renewable energy is among the renewable energy technologies with the greatest potential to scale up. The market potential for ORE technologies is currently growing and together with technical advances and prices developments, the sector will continue to develop and support the efforts towards climate neutrality by 2050.

Offshore wind is emerging as the technology with the most prominent role in the ORE sector, both in terms of technology maturity and installed capacity. Currently, there is a total of 15.6 GW of offshore wind installed in EU-27 Countries and 12.745 GW in the other European countries[50]. Looking at the European countries with coasts on the Atlantic Ocean, their contribution for the current European offshore wind capacity is the following: 2 MW from France; 25 MW from Ireland, 25 MW from Portugal and 5 MW from Spain located on the Canary Islands (WindEurope, Wind energy in Europe - 2021 Statistics and the outlook for 2022-2026). Looking at the near future, WindEurope's statistics predict that, in a realistic scenario, Europe will install 27.9 GW of offshore wind between 2022 and 2026 (WindEurope, Wind energy in Europe - 2021 Statistics and the outlook for 2022-2026).As per offshore wind cost of energy, current projection predicts a LCOE of 30-60 €/MWh for bottom-fixed solutions for 2050, according to the European Commission' report (European Commission, 2021).

The ETIPWind report (ETIPWind, 2021), indicates an average LCOE of €48/MWh for bottom-fixed solutions for 2030 (including the connection to the nearest onshore substation). To reach such LCOE values, this report considers that the main cost reductions affect the CAPEX, thanks to the increase in turbines' sizes, material efficiency and leaner designs, better installation techniques and grid technology improvements. Other drivers for cost reduction will be sufficient market volume to achieve economies of scale and the continuity of improvements in Operations and Maintenance (O&M). LCOE projections for 2050 show an average value of €37/MWh (ETIPWind, 2021).

The same ETIP Wind report expects an average LCOE of 64€/MWh by 2030 and 40€/MWh by 2050 for floating offshore wind. The main factor for cost reduction will be the evolution and maturity of floating technologies, which will allow for leaner floaters and improved mooring designs, as well as the industrialization of all the components in the floating technology. Other drivers are the optimization of manufacturing and assembly and moving from single units to large scale production (ETIPWind, 2021).

Ocean energy is reaching a level of maturity that makes it attractive to future applications, and the European supply chain is key in the technology's development, mainly in wave and tidal (An EU Strategy to harness the potential of offshore renewable energy for a climate). These are relatively stable and predictable technologies that can complement wind and solar Photovoltaic (PV), however the sector still struggles to create an EU market despite progress in development and demonstration (European Commission, 2020b).

Ocean Energy Europe "2030 Ocean Energy Vision" report predicts that by 2030 wave energy could reach a LCOE of 110€/MWh with a total of 494 MW of global installed capacity (Ocean Energy Europe, 2020a). Currently, wave energy did not reach the commercialization stage, with multiple concepts being explored: within the five devices deployed in Europe in 2021, four different technologies are present - oscillating water column, attenuator, point absorber and rotating mass (Ocean Energy Europe, 2020b).

[50] https://windeurope.org/intelligence-platform/product/offshore-wind-energy-2022-mid-year-statistics/

Tidal energy could reach 90€/MWh with a total of 2.39 GW of installed capacity by 2030 according to (Ocean Energy Europe, 2020a). As of 2021, there are 11.5 MW of operating capacity in Europe, with three devices deployed in 2021. The successful designs currently deployed are horizontal-axis turbines, vertical axis turbines and tidal kite.

Due to the level of maturity of both technologies, 2050 LCOE values are too uncertain to present at this stage. The first cost reduction is expected to come from Research and Development (R&D), where established "proof of concept" and array demonstratorsdemonstrators will build investors' confidence and secure cheaper capital. Further on, large-scale deployment will produce the most significant cost reductions (ETIPOcean, 2020).

Amongst all the offshore renewable energies, floating photovoltaic (PV) is the furthermost from a commercial state. Offshore PV installations present far more challenges than freshwater ones and at the moment the technology is still in the early R&D phase with small scale pilots (ETIPOcean, s.d.). According to a report from DNV GL, as of 2020, the LCOE of offshore PV systems was at around 354 €/MWh, however with technologic developments this value is estimated at €50 €/MWh by 2030 and 40 €/MWh by 2050 for an installation in the Netherlands (Bellini, 2020).

More recently, Oceans of Energy has announced the deployment of a 3 MW full-scale demonstrator in the near future off the Belgian coast in the North Sea which, according to the company, will bring the cost down to 150 €/MWh with the prospect of achieving 50 €/MWh in future projects (Bellini, 2021).

2.2. Scenario definition

After selecting the potential spots for offshore renewable deployment from Task 1, the production scenarios for offshore renewables deployment in the European Atlantic region are defined. There are two set of scenarios for both 2030 and 2050: a current pathway scenario and an ambitious one.

The baseline to define the scenarios is the Offshore Renewable Energy Strategy by the European Commission (European Commission, 2020). Adding to that, it is also consideredthe deployment targets for offshore renewables set by each of the analysed countries on their National Energy and Climate Plans (NECP). Targets for offshore capacity set by European associations such as WindEurope and Ocean Energy Europe are also considered, together with the contribution of each technology to the electricity mix in each country object of analysis.

The current pathway scenario is defined by looking into published objectives or predictions. Due to the high potential available in the Atlantic region, for the ambitious scenario this study considers in some cases doubling the target defined on the current pathway scenario.

The European Commission's Offshore Renewable Energy strategy released in 2020 sets the objective of at least 60 GW of offshore wind and 1 GW of ocean energy installed capacity in Europe by 2030 (European Commission, 2020), being mentioned on the "*Progress on competitiveness of clean energy technologies*" report that the Atlantic Ocean will contributecontribute with 11.1 GW to the offshore wind target (European Commission, 2021). For 2050, European Commission's Offshore Renewable Energy strategy aims at a total installed capacity of at least 300 GW of offshore wind and 40 GW of ocean energy.

Looking at sectoral associations, Wind Europe expects a total of 450 GW of offshore wind by 2050 (WindEurope, 2019a). Regarding ocean energy technologies, Ocean Energy Europe predicts that on a high growth scenario, Europe will achieve 2.2 GW of tidal stream energy and 0.43 GW of wave energy by 2030 (Ocean Energy Europe, 2020a). By 2050, the same report states that it is possible to reach 100 GW of ocean energy in Europe.

The assumptions which uderpin the calculations are based on the information available until September 2022.

2.2.1. Current pathway scenario installed capacity

2.2.1.1 Offshore wind energy

TABLE 2-1 : INSTALLED CAPACITY OF OFFSHORE WIND FOR 2030 AND 2050 FOR THE CURRENT PATHWAY SCENARIO.

Year	France	Ireland	Portugal	Spain	TOTAL ATLANTIC
2030	3.9 GW	1.0 GW	6.0 GW	3.0 GW	**12.4 GW**
2050	32.8 GW	15.0 GW	9.0 GW	7.0 GW	**61.8 GW**

Regarding France, the value for 2030 is a result of the announcement of RTE' Energy Pathways for 2050 (RTE, 2021) minus the two 250 MW farms announced for the Golf du Lion in the Mediterranean Sea. For 2050, the capacity defined by the Mediterranean study (7.2 GW) (European Commission , 2020) was subtracted from the 40 GW for France vision from Wind Europe (Wind Europe, 2019).
The values proposed for Ireland for 2030 and 2050 are the targets indicated by Irish Government representatives. The targets are a fraction of the announced for the whole country of 7 GW for 2030 and 37 GW by 2050 (North Seas Energy Cooperation, 2022).
The value assumed for offshore wind in Portugal by 2030 is the minimal capacity announced for a 2023 tender (Durakovic, 2022b). The 2050 value is the one that guarantees the same share in the electricity mix as in 2030. However, as of January 2023, it was announced that Portugal expects to launch its first offshore wind power auction by the end of 2023, aiming to reach 10 GW of installed capacity by 2030 (Goncalves, 2023). This higher ambition is expected to lead to higher social welfare and CO_2 reduction.
Spain has as target the deployment of 3 GW of offshore wind by 2030 (Ministry for Ecological Transition and the Demographic Challenge, 2022): since some of the announced projects are in the Mediterranean Sea and Canary Island, half of this target is assumed as the current pathway for Spain in the continental Atlantic Ocean coast by 2030. Regarding 2050, it is considered as target the difference between the total country capacity (11 GW) and the Mediterranean capacity (6 GW) from the Mediterranean study (European Commission , 2020).

2.2.1.2 Ocean energy

In the scope of this study, only wave and tidal will be addressed under ocean energy. Due to the lower maturity level of these technologies, there are not many countries or regional specific targets announced. Nevertheless, the European Commission announced a European target of more than 1 GW by 2030 and 40 GW by 2050, which is an indication of the commitment towards the development of Ocean Energy (European Commission, 2020).

TABLE 2-2: INSTALLED CAPACITY OF OCEAN ENERGY FOR 2030 AND 2050 FOR THE CURRENT PATHWAY SCENARIO.

Year	France	Ireland	Portugal	Spain	TOTAL ATLANTIC
Wave 2030	0.1 GW	0.1 GW	0.1 GW	0.1 GW	**0.4 GW**
Wave 2050	3.0 GW	0.5 GW	0.5 GW	1.0 GW	**5.0 GW**
Tidal 2030	1.0 GW	0.2 GW	-	-	**1.2 GW**
Tidal 2050	5.9 GW	1.0 GW	-	-	**6.9 GW**

Wave energy values for the current pathway scenario were taken from the OEA-IEA "Socio-economic impact of Ocean Energy development: GVA and job assessment in 2050" (Innosea, 2021) with exception of Ireland and 2030 France that presented 0 GW capacity. Because 0 GW is not realistic for 2030, the assumed values for 2030 in France and Ireland in the current path scenario will be the same as Portugal and Spain (0.1 GW), for Ireland in 2050 it is considered the same value as in Portugal (being the closest country in terms of dimensions).

There are no selected spots suitable for tidal energy in Portugal and Spain, leading to no proposed capacity. Looking for France in 2030, it is considered 1GW based on the announced project 1GW of tidal for Raz Blanchard strait (Hydropower & Dams, s.d.). For 2050 is considered the same value as the OEA-IEA "Socio-economic impact of Ocean Energy development: GVA and job assessment in 2050" (Innosea, 2021).

There are not specific objectives in terms of tidal capacity for Ireland, as so, the current pathway scenario considers that by 2030 and 2050 it will be installed enough capacity to guarantee the same contribution to the electricity mix as in France.

2.2.1.3 Floating solar photovoltaics

Offshore floating photovoltaic (PV) is still on the Research & Development (R&D) stage with only limited capacity installed worldwide (DNV GL, 2022a). Given the early stage of development, it is difficult to estimate future developments without having a clear vision on how the technology will evolve into guaranteeing its feasibility.

To define the floating PV capacity for the production scenarios it is considered the resource availability (solar radiation) with some limitations on the wave hight and the water depth. Ireland and Spain did not present any side that complies with these limitations. Table 2-3 presents the capacity of offshore floating photovoltaic for the ambitious scenario.

TABLE 2-3: INSTALLED CAPACITY OF OFFSHORE FLOATING PHOTOVOLTAIC ENERGY FOR 2030 AND 2050 FOR THE CURRENT PATHWAY SCENARIO

Year	France	Ireland	Portugal	Spain	TOTAL ATLANTIC
Solar 2030	0.2 GW	0	0.1 GW	0	**0.3 GW**
Solar 2050	2.0 GW	0	1.0 GW	0	**3.0 GW**

2.2.2. Ambitious scenario installed capacity

There is a high potential for offshore renewable energy in the Atlantic Ocean, and in specific in the European coast as concluded in the previous chapter. The values presented for the ambitious scenario come from objectives and ideals published by sectoral associations, by tenders or when no information was found or by assuming a doubling of the current scenario capacity.

2.2.2.1 Offshore wind energy

The installed capacity of offshore wind energy for the ambitious scenario is presented in Table 2-4.

TABLE 2-4: INSTALLED CAPACITY OF OFFSHORE WIND FOR 2030 AND 2050 FOR THE AMBITIOUS SCENARIO.

Year	France	Ireland	Portugal	Spain	TOTAL ATLANTIC
2030	11.0 GW	2.0 GW	8.0 GW	3.0 GW	**24.0 GW**
2050	40.0 GW	17.0 GW	12.0 GW	7.0 GW	**76.0 GW**

Regarding France, 11 GW are set for 2030 by substracting the 9 GW value estimated by the Mediterranean study (K. Staschus et al., 2020) from the country's goal of achieving 20 GW by 2030 (Pacte éolien en mer entre l'Etat et la filière, 2022). 11 GW of offshore wind by 2030 on the French Atlantic implies the deployment of extra 5.2 GW from the current ongoing and predicted projects[51]: for this reason this target seams a reasonable value for the ambitious scenario. For 2050, the target set is 40 GW for the French Atlantic, as this is the proposed value by WindEurope report (WindEurope, 2019a), and goes above the French government target of 40 GW for the whole country (Mediterranean plus Atlantic waters) (Pacte éolien en mer entre l'Etat et la filière, 2022).
For Ireland, the ambitious scenario considers that offshore wind from the Irish Atlantic doubles its share in the electricity mix achieving 2 GW in 2030. For 2050, it is considered 17.0 GW of offshore wind for the Atlantic following the highest value from the targets of 15 and 17 GW for 2050 by the same source as the current pathway scenario.
Looking at Portugal, a value of 8 GW is considered for offshore wind for 2030, following the announcement by Portuguese Government officials of a 6 to 8 GW tender of offshore wind to be launch in 2023 ("Governo quer leilão de eólico offshore 'grande' com mínimo de 6 a 8 GW em 2023"). For 2050, 12 GW is set for offshore wind in Portugal, which is the necessary capacity to maintain a similar contribution of offshore wind in the electricity mix.
Lastly, for Spain it is set a deployment of 3 GW on the Spanish Atlantic Ocean by 2030. 3 GW is the national target for offshore wind for all Spain, including the Mediterranean and Canary Islands (*Roadmap for the development of offshore wind and marine energy in Spain*, 2022), thus considering the same capacity deployment solely for the Spanish Atlantic is a significant ambitious target. The 7 GW of offshore wind by 2050 for the Spanish Atlantic area comes from subtracting the 6 GW considered for the Mediterranean sea (European Commission , 2020) from the 13 GW envisioned by Wind Europe (Wind Europe 2019) for the whole Spain Ocean energy.

2.2.2.2 Ocean energy

TABLE 2-5: INSTALLED CAPACITY OF OCEAN ENERGY FOR 2030 AND 2050 FOR THE AMBITIOUS SCENARIO.

Year	France	Ireland	Portugal	Spain	TOTAL ATLANTIC
Wave 2030	0.3 GW	0.2 GW	0.2 GW	0.2 GW	**0.9 GW**
Wave 2050	4.5 GW	1.0 GW	1.0 GW	2.0 GW	**8.5 GW**
Tidal 2030	2.0 GW	0.3 GW	-	-	**2.3 GW**
Tidal 2050	6.9 GW	1.1 GW	-	-	**8.0 GW**

[51] https://www.eoliennesenmer.fr/presentation

The capacity for wave for the ambitious scenario is the one that implies doubling the installations when compared to the current pathway scenario, with exception for France whose values is the same that guarantees the same share on the electricity mix as in 2030. For tidal energy, the 2 GW value for 2030 in France was also taken from the announced project for Raz Blanchard strait (Hydropower & Dams, s.d.) that ambitions to develop and extra 1GW with the conclusion of the first 1 GW. For 2050, because the current pathway scenario is already ambitious an extra 1GW was added to set the ambitious scenario.
The ambitious scenario for tidal energy for Ireland was defined the same form as in the current pathway scenario, by considering the same share in the electricity mix as in France.
The proposed targets imply that the Atlantic region could contribute with 3.4 GW of ocean energy by 2030 and 12.5 GW by 2050.

2.2.2.3 Floating solar photovoltaics

As in the current pathway scenario, there is not many indicators that could guide into defining the capacity to be installed of offshore floating solar photovoltaics on an ambitious scenario. To set the scenario, it was added to the current pathway scenario an extra 0.1 GW of capacity in 2030, 0.5 GW in Portugal for 2050 and 1 GW for France in 2050. It is added more capacity in France in 2050 due the bigger dimension and consumption of France when compared to Portugal. Table 2-6 presents the ambitious scenario for offshore floating PV.

TABLE 2-6: INSTALLED CAPACITY OF OFFSHORE FLOATING PHOTOVOLTAIC ENERGY FOR 2030 AND 2050 FOR THE AMBITIOUS SCENARIO

Year	France	Ireland	Portugal	Spain	TOTAL ATLANTIC
Solar 2030	0.3 GW	0.0 GW	0.2 GW	0.0 GW	**0.5 GW**
Solar 2050	3.0 GW	0.0 GW	1.5 GW	0.0 GW	**4.5 GW**

2.3. Levelized Cost Of Energy of offshore technologies in the selected areas

The Levelized Cost of Energy (LCOE) is a measure of the average net present cost of electricity generation for a generating plant over its lifetime. When computing the LCOE, two main types of expenditures can be identified:

- CAPEX (Capital Expenditures) are funds used by a company to acquire or upgrade physical assets.
- OPEX (Operational Expenditures) are the costs associated with the operation and maintenance of the plant.

The LCOE is computed using the following formula:

EQUATION 5

$$LCOE = \frac{\sum_{t=0}^{n-1} \frac{CAPEX_t + OPEX_t}{(1+a)^t}}{\sum_{t=1}^{n-1} \frac{P * CF * 8760 * (1-d)^{t-1}}{(1+a)^t}}$$

Where:

- a is the discount rate of the investment;
- n is the expected lifetime of the power plant;
- $CAPEX_t$ is the net investment expenditure in year t;
- $OPEX_t$ is the net operational and maintenance expenditure in year t;

- P is the installed capacity of the power plant;
- CF is the yearly capacity factor of the power plant;
- d is the degradation factor which takes into account the ageing of the power plant and the consequent reduction of the output power after the first operational year.

The LCOE calculation object of this study relies on site dependent parameters: this procedure facilitated the computation for the different offshore technologies, being less dependent on variables that are not intrinsically linked with the topography of the site at stake.

The parameters that oriented the cost computation are the water depth, the distance from nearest adequate port and the distance from the electrical onshore substation. The transmission costs, for example, result from, among other parameters, the distance from the closest electrical onshore substation, the mooring lines' costs are modelled on the water depth and installation costs on the distance from an adequate port (a port with the necessary infrastructures and dimension).

Onshore and offshore transmission asset connection costs (offshore and onshore substations and export cables) are integrated in this study.

Decommissioning cost is computed as a fixed percentage of all the other cost items.

Finally, the discrimination between fixed and floating offshore wind, is operated taking into account the water depth of the site.

Table 2-7: Cost modelling approach per renewable energy technology (Martinez and Iglesias, 2022)

Technology	CAPEX/OPEX approach	LCOE approach
Offshore wind	Selection between fixed and floating offshore wind is made upon the water depth. The cost of the turbine and the structure is computed as a function of the installed capacity. Installation costs consider the distance from the nearest port and differentiate for the kind of vessel employed for the two technologies (tugboat for floating and jack-up vessel for fixed offshore wind). Transmission costs take into account the distance from the closest onshore electrical substation. A distinction between HVAC and HVDC is also considered. Mooring lines' costs are modelled according to the water depth and a coefficient to account for extra length of catenary mooring. Decommissioning is calculated as a fix percentage of the total costs. OPEX is computed as a fix annual percentage of the CAPEX.	LCOE values for 2030 and 2050 are computed by means of a learning rate.
Wave	The cost of the turbine and the structure is computed as a function of the installed capacity.	LCOE values for 2030 and 2050 are computed by means of a learning rate.

	The installation of the wave energy devices foresees a tugboat. Transmission costs take into account the distance from the closest onshore electrical substation. A distinction between HVAC and HVDC is also considered. Mooring lines' costs are modelled according to the water depth and a coefficient to account for extra length of catenary mooring. Decommissioning is calculated as a fix percentage of the total costs. OPEX is computed as a fix annual percentage of the CAPEX.	
Tidal	The rotor cost is computed as a function of the diameter. The cost of the foundations differs on the water depth. Transmission costs take into account the distance from the closest onshore electrical substation. A distinction between HVAC and HVDC is also considered. A jack-up vessel is envisaged for the installation process. Decommissioning is calculated as a fix percentage of the total costs. OPEX is computed as a fix annual percentage of the CAPEX.	LCOE values for 2030 and 2050 are computed by means of a learning rate.
Floating PV	The cost of the floaters is computed as a function of the installed capacity. Transmission costs take into account the distance from the closest onshore electrical substation. A distinction between HVAC and HVDC is also operated. Mooring lines' costs are modelled according to the water depth and a coefficient to account for extra length. A tugboat is assumed for the installation process. Decommissioning is calculated as a fix percentage of the total costs. OPEX is computed as a fix annual percentage of the CAPEX.	LCOE values for 2030 and 2050 are computed by means of a learning rate.

LCOE projections for 2030 and 2050 are produced by means of the experience curve (Pennock et al., 2022), whose formula can be written as:

EQUATION 6

$$C(x_t) = C(x_0) \cdot \left(\frac{x_t}{x_0}\right)^{-b}$$

Where:

- x_0 is the capacity at time $t = 0$;
- $C(x_0)$ is the cost of a unit at time $t = 0$;
- x_t is the cumulative capacity at time t;
- $C(x_t)$ is the cost of a unit at time t;
- b is the learning rate parameter.

The appropriate learning rate for each of the different technologies is dependent on the level of maturity of the technology. The cumulative capacity considered at different time horizons t is retrieved, for offshore wind, from Wind Europe Intelligence Platform[52] for 2020, from (WindEurope, 2022) and The EU Offshore Renewable Energy Strategy (2020) for 2030 and 2050 respectively. For wave and tidal energy (Ocean Energy Europe, 2021), (Ocean Energy Vision 2030, Ocean Energy Europe, 2020) and The EU Offshore Renewable Energy Strategy (2020) are the baseline upon which the cumulative capacity is estimated.

2.3.1. LCOE results per technology

LCOE values are calculated per country following the methodology explained in the previous section and the available spots selected in Task 1. Figures from Figure 34 to Figure 40 show the LCOE levels in €/MWh per technology.

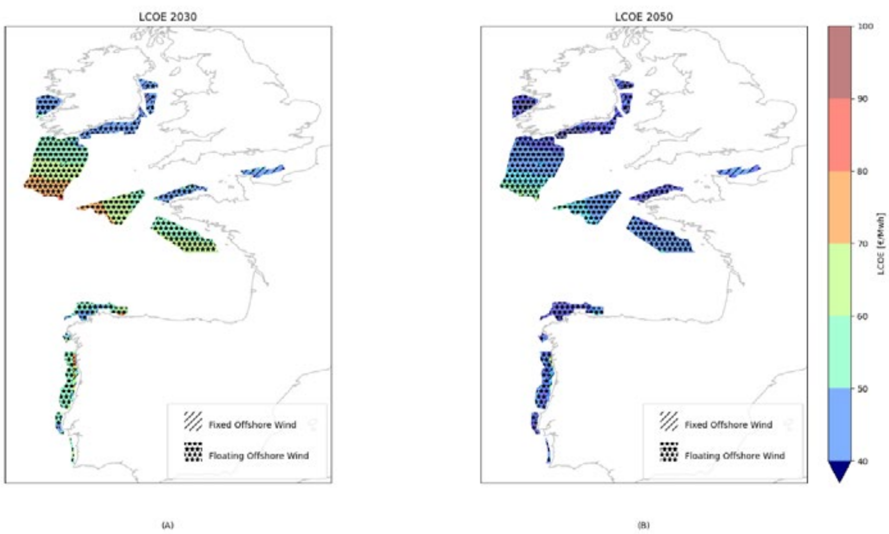

FIGURE 34: A) LCOE OFFSHORE WIND 2030 AND B) LCOE OFFSHORE WIND 2050

Figure 34 A*)* and *B)* shows the average LCOE values for offshore wind in 2030 and 2050, for both fixed and floating. For 2030, given the depth of the Atlantic Ocean, floating offshore wind might be the best solution, unless huge improvements in fixed offshore wind capable of reaching water depths up to 80-100 m. Nevertheless France, in correspondence of Le Havre area, appears to be more suitable for fixed offshore wind in terms of average LCOE values, with only two spots for floating. In Spain, Galicia might reach by 2030

[52] https://windeurope.org/intelligence-platform/

competitive LCOE values for floating offshore wind, ranging between 40 and 50 €/MWh. In Portugal, in areas with shallow waters where fixed would be a viable option, the LCOE reaches a maximum of 85 €/MWh, due to the limited resource availability. Moving farther from the shore, in deeper waters, the LCOE gets lower thanks to the higher wind resource, with a minimum of 45 €/MWh for floating offshore wind.

In 2050 increased offshore wind deployment in the Atlantic Ocean and in other regions of the world is expected to drive down costs and increase the efficiency in the rollout of floating wind turbines: Figure 34 *b)* shows reduced values of LCOE, varying between 30 and 60 €/MWh.

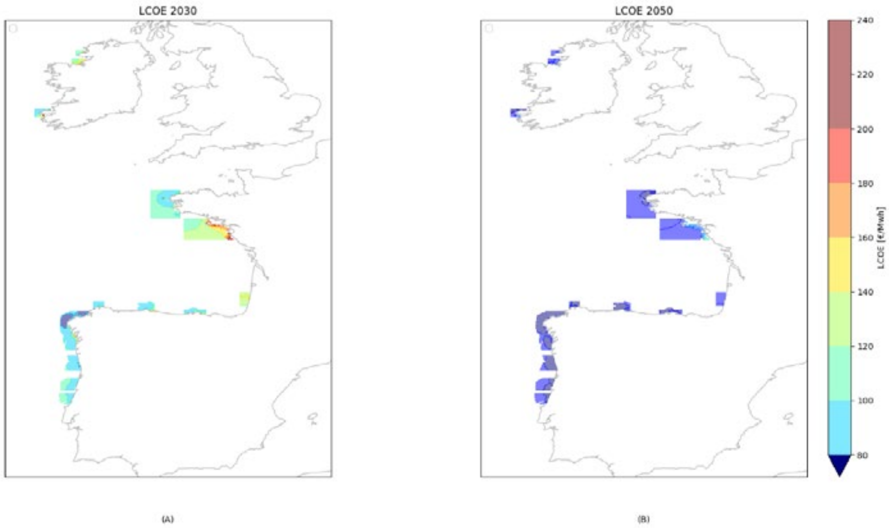

FIGURE 35: A) LCOE WAVE 2030 AND B) LCOE WAVE 2050

Figure 35 A*) and B)* presents the results obtained for wave energy. Waters off the coast of Portugal and Spain (especially Galicia) are the preferred location for wave energy, with average LCOE values in 2030 that might range from 70 to 100 €/MWh, as the water depth increases approximately from 50 up to 150 meters. France also registers some economically viable areas for wave in Bretagne, with LCOE values in 2030 ranging between 90 and 100 €/MWh: in this case the increase on the LCOE is registered concurrently to an increase in the water depth of 100 meters. Nantes' area presents less favorable conditions in terms of LCOE values, starting from 100 to reach 220 €/MWh in some locations with really shallow waters (around 10 meters). Spain and south-west Ireland offer some spots where 2030 LCOE values are comparable with those of Bretagne. North-west Ireland instead shows higher LCOE values, despite shallower waters, due to the lower potential in this area.
In Figure 35 B*)* are illustrated LCOE values for wave in 2050: this analysis examined how wave energy costs will reduce as the technology is likely to develop. LCOE projections for this technology range from a minimum of 35 €/MWh to a maximum of 100 €/MWh.

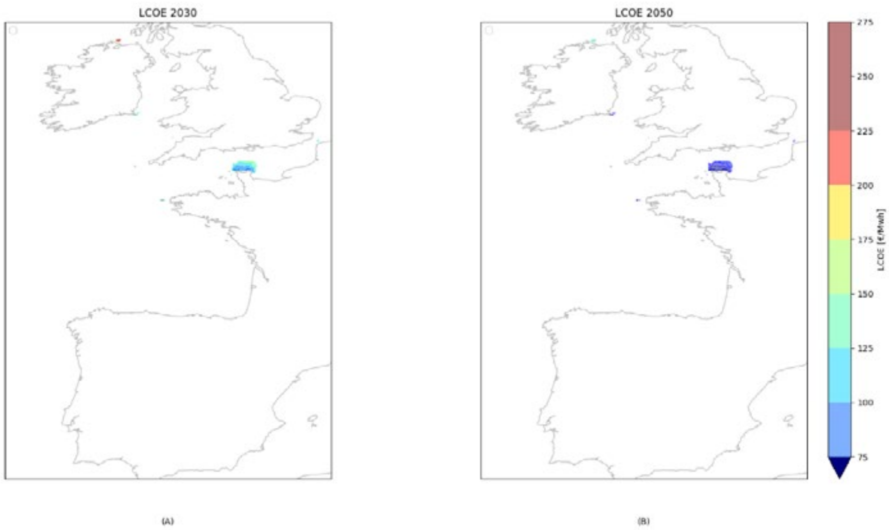

FIGURE 36: A) LCOE TIDAL 2030 AND B) LCOE TIDAL 2050

Figure 36 *A)* and *B)* shows the results obtained for tidal for 2030 and 2050: for this technology France (more precisely, the Le Havre area) might offer a suitable spot, with average values of LCOE ranging between 90 and 135 €/MWh in 2030.

Regarding 2050, the same observations made for wave energy apply for tidal: Figure 36 B*)* shows the projections obtained, which expect LCOE to drop between 50 and 90 €/MWh.

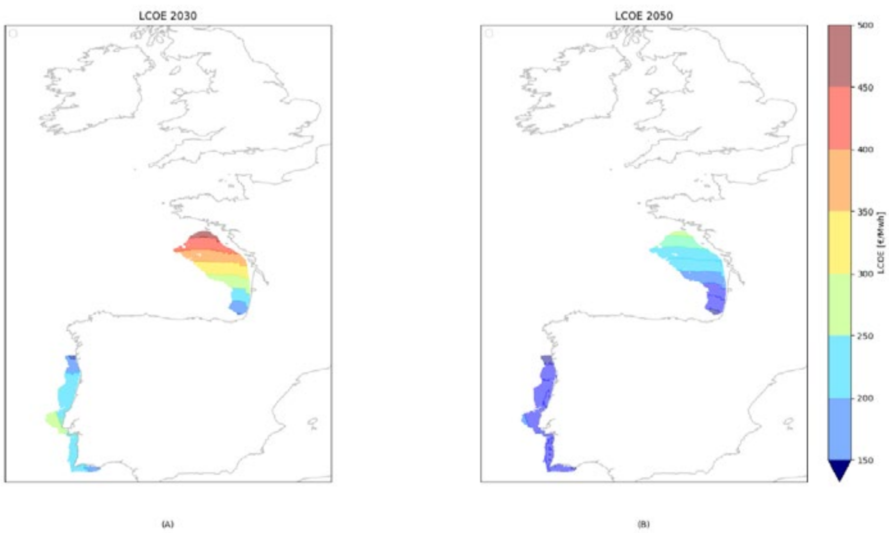

FIGURE 37: A) LCOE FLOATING PV 2030 AND B) LCOE FLOATING PV 2050

Finally, Figure 37 *A)* and *B)* shows the results for floating PV for the selected sites: Portugal seems to be the preferred location for floating PV, with average LCOE values ranging between 135 to 225 €/MWh in 2030, for locations situated in proximity of the coast. Moving farther from the shore, the LCOE increases up to 280 €/MWh. France shows a wider range of LCOE values, due of the difference in terms of potential availability.

While floating PV is already well advanced in fresh water, currently in Europe there are just a few pilots aiming at upscaling this concept in sea waters. In this case, the range of variation of LCOE values in 2050 (see Figure 37 B*)*) is wider, varying between 80 and 275 €/MWh, since it reflects the difference in terms of potential (as observed for 2030).

2.3.2. Hybrid power plants

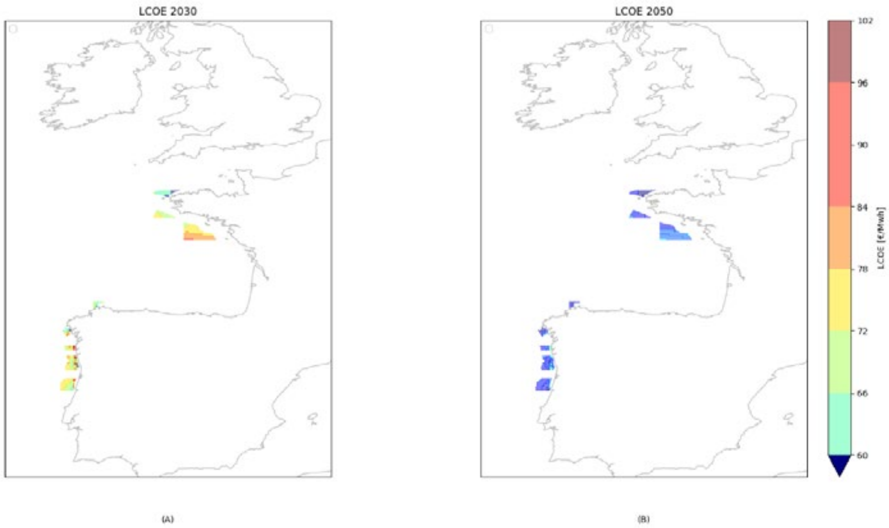

FIGURE 38: A) LCOE WIND/WAVE 2030 AND B) LCOE WIND/WAVE 2050

This study also investigates the possibility of coupling wind with another technology (either wave, tidal or solar), in those areas where the selected sites for the two technologies at stake overlap. Figure 38 *A)* and *B)* presents the average LCOE values obtained for the combination wind-wave, for 2030 and 2050.

The map indicates that in Portugal and Spain (Galicia region), for water depth values between 50 and 120 meters, this mix might lead to an LCOE, in 2030, of approximately 70 €/MWh. France shows average LCOE values ranging from 60 to 80 €/MWh.
Figure 38 B*)* shows the results forecasted for the combination wind/wave in 2050. The progress expected to be achieved by both technologies is reflected in a decrease of the average LCOE values, ranging between a minimum of 40 €/MWh to a maximum of 60 €/MWh.

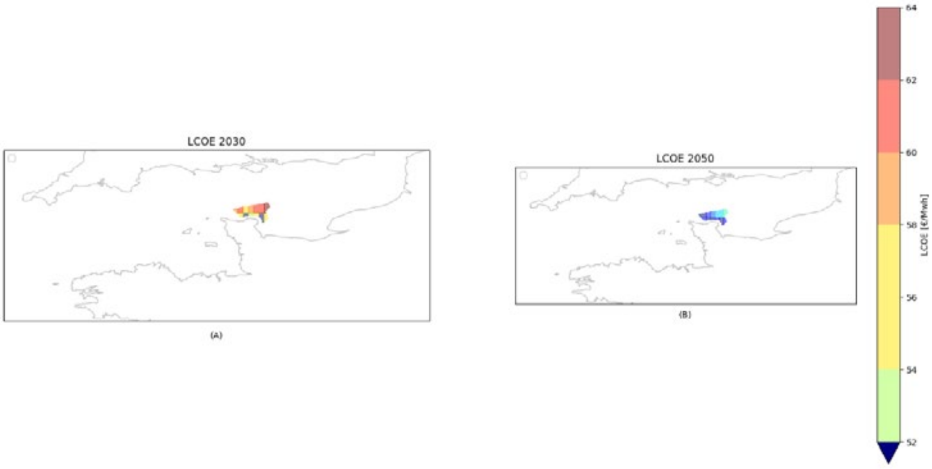

FIGURE 39: A) LCOE FOR WIND/TIDAL 2030 AND B) LCOE FOR WIND/TIDAL 2050

Figure 39 A*)* and B*)* shows the average LCOE values for the combination wind-tidal in 2030 and 2050. As it is possible to notice, only one of the selected spots shows potential for this particular hybrid plant: it is located in the Le Havre area, where LCOE values are quite homogenous, varying from 50 to 65 €/MWh in 2030.

The same considerations made for the combination wind/wave apply to wave/tidal which for the suitable spot identified foresee quite homogenous average LCOE values in 2050, ranging between 40 and 50 €/MWh (see Figure 39 *B)*).

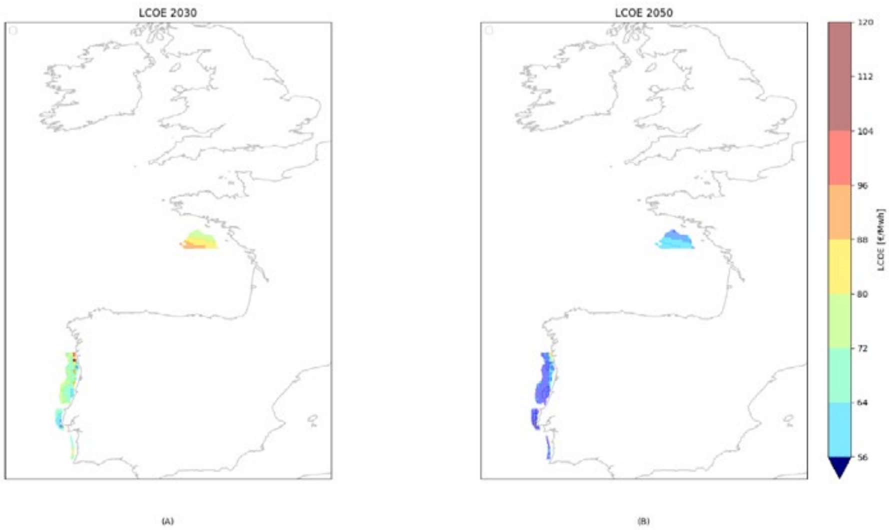

FIGURE 40: A) LCOE FOR WIND/FLOATING PV IN 2030 AND B) LCOE FOR WIND/FLOATING PV IN 2050

Finally, Figure 40 *A)* and *B)* illustrates the results obtained for the combination wind-floating PV in 2030 and 2050. Portugal in this case might reach by 2030 quite homogenous

values of LCOE (between 60 and 70 €/MWh). Another suitable spot is located in France, with slightly higher values ranging between 75 and 90 €/MWh.
Among all combinations, this is the one leading to the highest predictions for average LCOE values in 2050 (between 35 and 80 €/MWh).

2.3.3. Cost curves

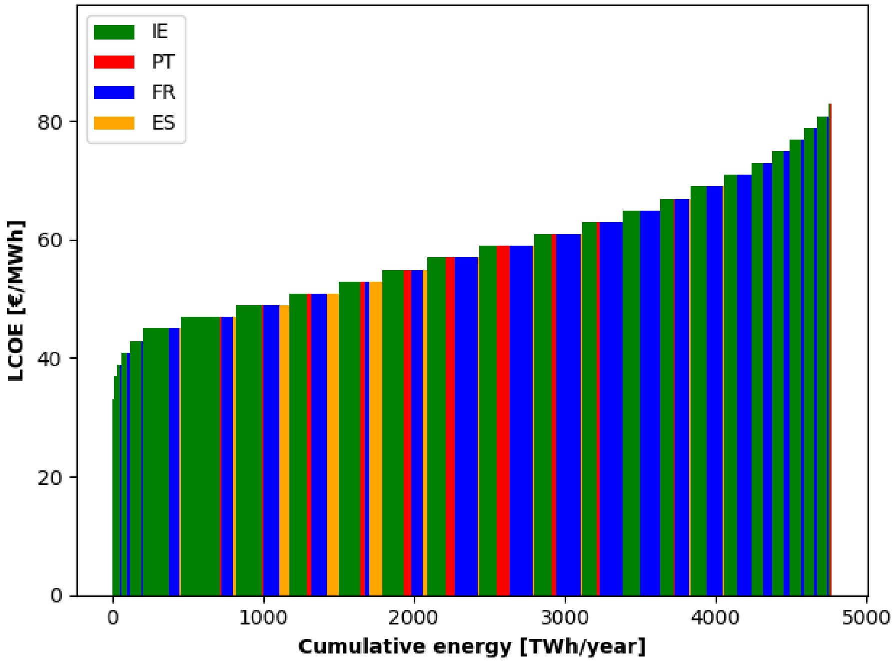

FIGURE 41: COST CURVES OFFSHORE WIND 2030

For the main offshore energy renewable technologies (offshore wind, wave, tidal and floating PV), this section analyzes the LCOE against the estimated cumulative energy potential available in each country object of study.
Figure 41 shows the cost curves for offshore wind (both fixed and floating) in 2030. Amongst all countries, Ireland is the one showing the most potential in correspondence with low LCOE values (between 30 and 50 €/MWh). In 2050 (Figure 42), LCOE levels are lower: as observed in section 2.3.1, this is attributable to the assumption of maturity increase of floating offshore wind technologies.

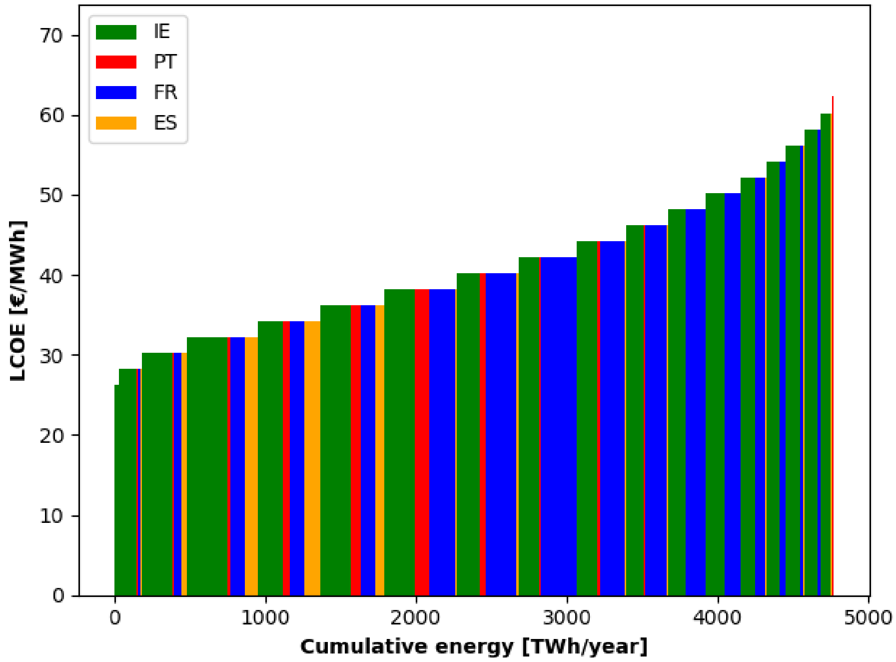

FIGURE 42: COST CURVES OFFSHORE WIND 2050

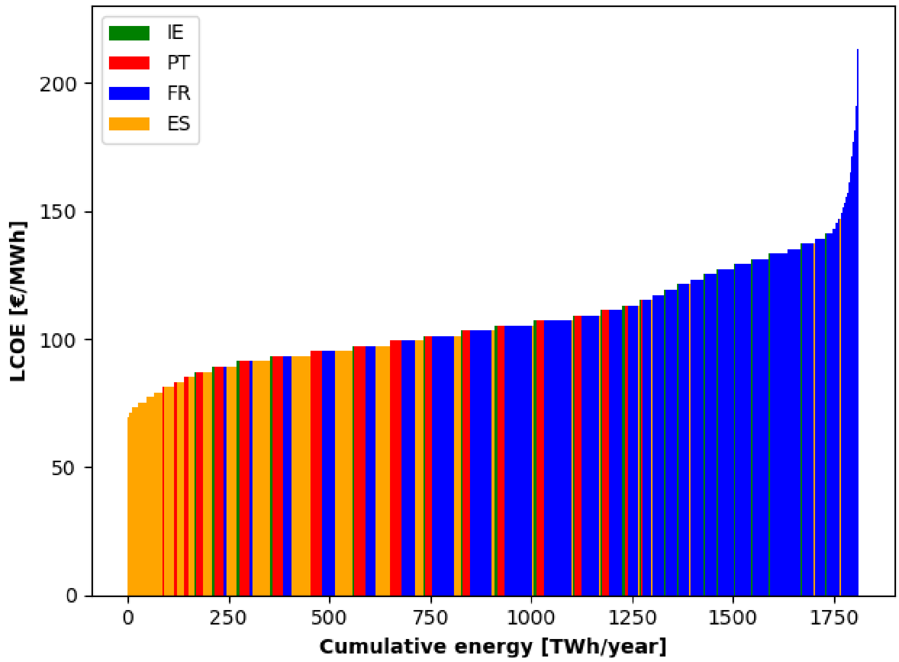

FIGURE 43: COST CURVES WAVE 2030

Cost curves for wave in 2030 and 2050 are presented in Figure 43 and Figure 44. The majority of the potential at the lowest LCOE is offered by Spain: in 2030 for values between 70 and 80 €/MWh, Spain cumulates circa 100 TWh per year. Portugal is the country showing LCOE values comparable with Spain, but for less cumulated potential. France shows high potential for a higher LCOE range (between 100 and 200 €/MWh). Ireland shows low potential for wave, for the selected areas. In 2050, the potential offered by France is available at decreased LCOE values (between 50 and 70 €/MWh), since costs for wave energy devices are expected to lower between 2030 and 2050.

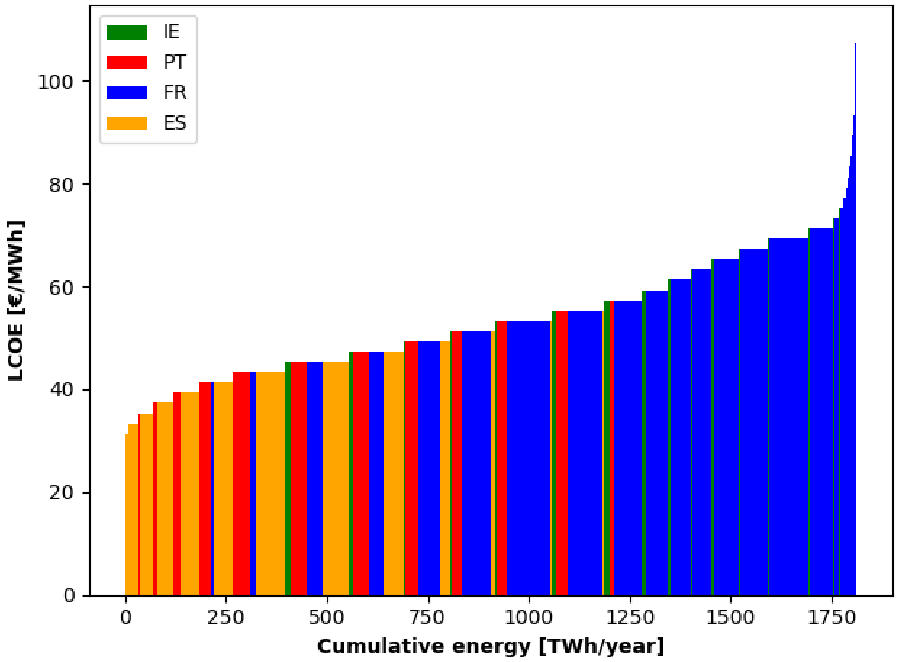

FIGURE 44: COST CURVES WAVE 2050

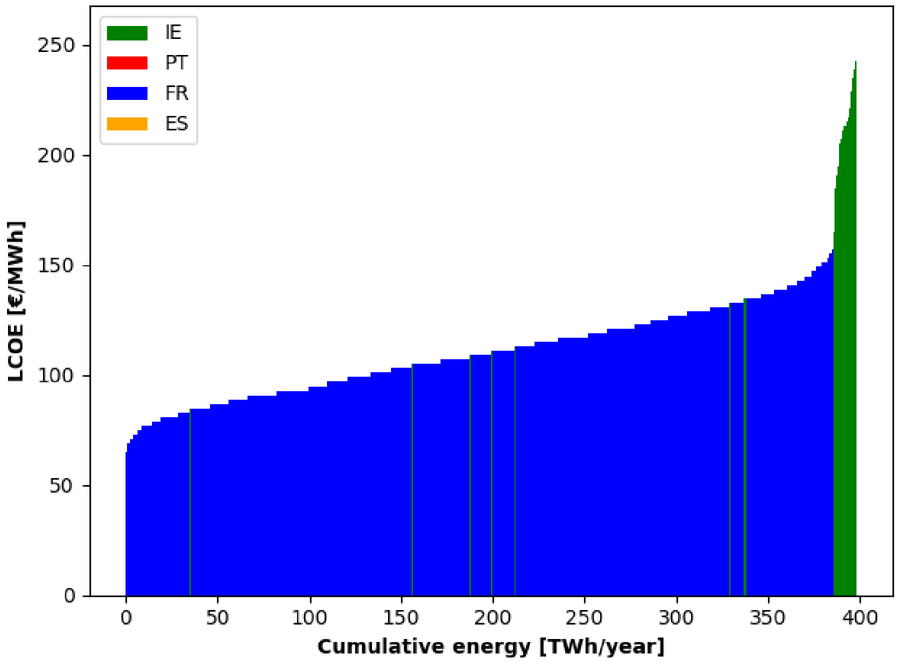

FIGURE 45: COST CURVES TIDAL 2030

Figure 45 shows the results obtained for tidal in 2030. Most of the identified suitable spots for this technology are located in France: here LCOE values range from 70 up to 150 €/MWh, as the cumulated energy reaches 380 TWh annually. The only suitable identified spot in Ireland enables to cumulate roughly 10 TWh annually, with LCOE values higher than France. The same considerations made for wave energy also apply for tidal: costs are expected to decrease significantly between 2030 and 2050. Figure 46 shows the results for tidal in 2050 were the LCOE values for tidal for France remains below 100 €/MWh: these values are higher than those registered for wave and significantly above those of offshore wind for the same year.

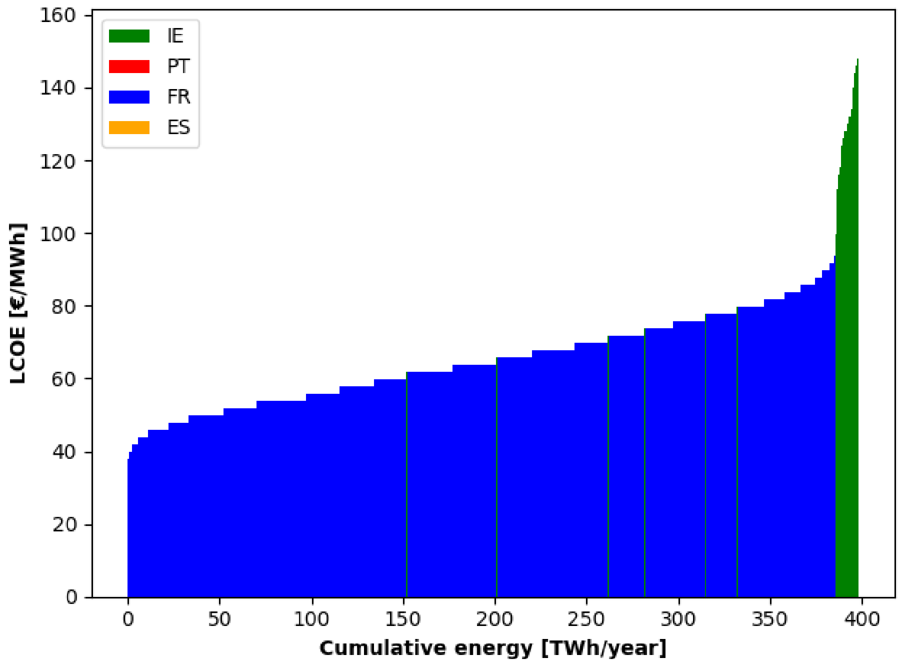

FIGURE 46: COST CURVES TIDAL 2050

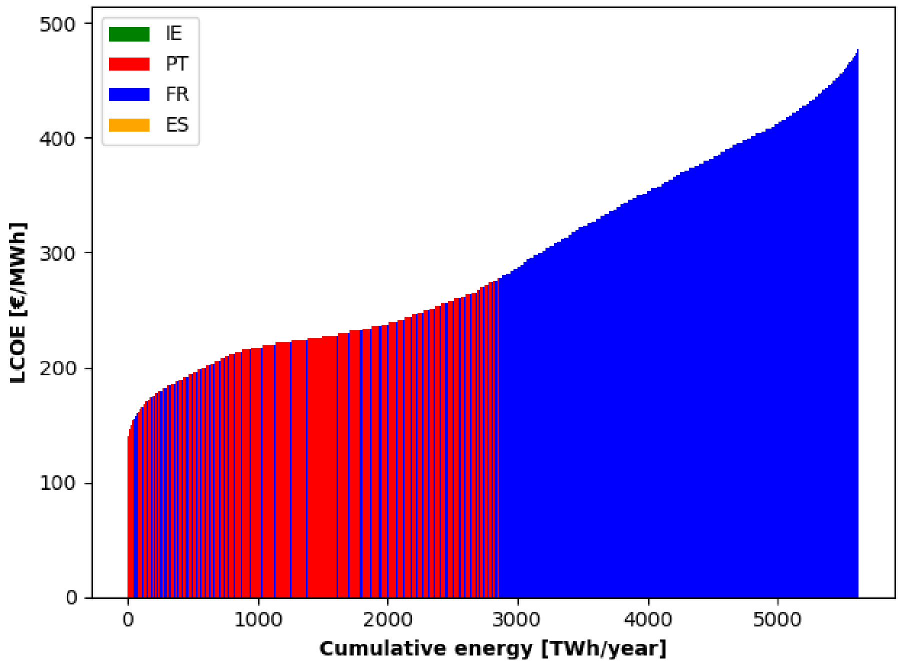

FIGURE 47: COST CURVES FLOATING PV 2030

Figure 47 shows the results obtained for floating PV in 2030: floating PV in Portugal seem to be economically more viable than France, with LCOE values below 300 €/MWh. In 2050 (Figure 48) this value remains slightly above 150 €/MWh.

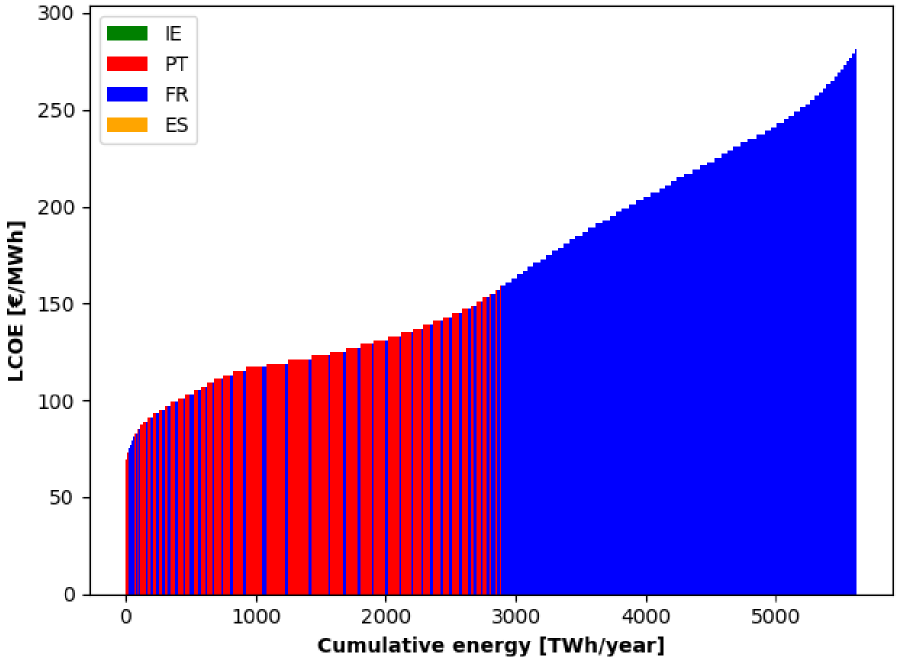

FIGURE 48: COST CURVES FLOATING PV 2050

2.4. Scenarios

2.4.1. Current pathway production scenario

From the LCOE maps from section 2.3 and the capacity established for each country Table 2-1, Table 2-2 and Table 2-3, results the current pathway offshore production scenarios for 2030 and 2050, presented in Figure 49. Each scenario is defined by choosing production blocks with low LCOE and considering the demand centres of the country.
Mixed technology areas are the selected choice in areas where the LCOE is lower in comparison of the LCOE of individual technologies.

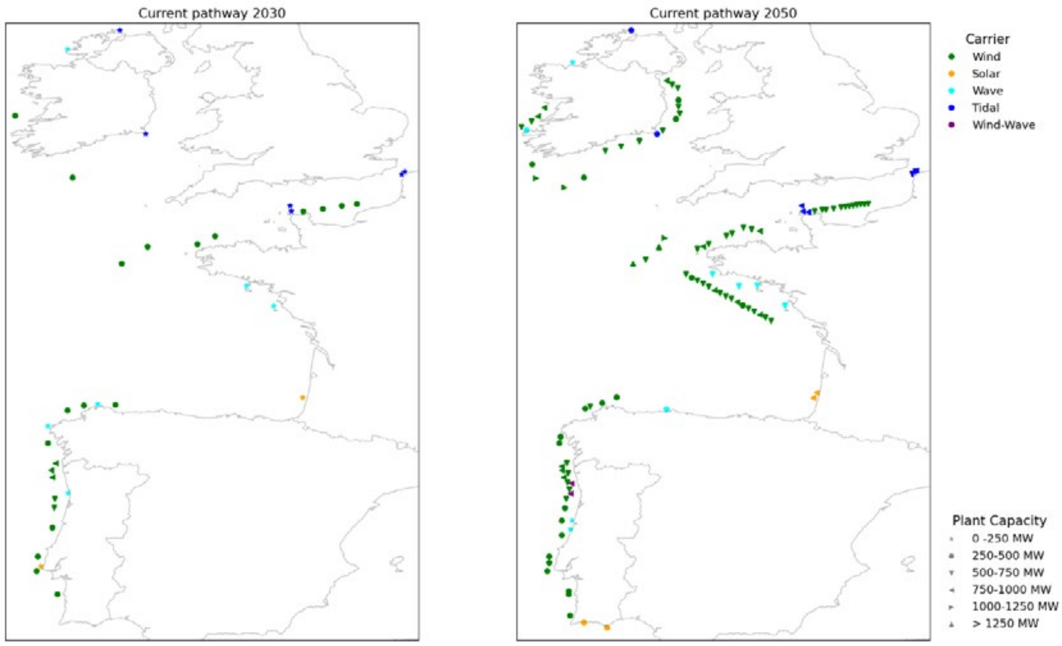

FIGURE 49 : 2030-2050 CURRENT PATHWAY OFFSHORE PRODUCTION SCENARIO FOR THE ATLANTIC REGION

2.4.2. Ambitious offshore production scenario

To produce the Ambitious Offshore Production Scenarios it is considered the installed capacity that is presented in Table 2-4, Table 2-5 and Table 2-6, and the LCOE maps presented in section 2.3. Figure 50 presents the Ambitious Offshore Production Scenario for the Atlantic Region for 2030 and 2050 respectively. The scenarios were defined similarly to the current pathway ones, by choosing production blocks with low LCOE and considering the demand centres of the country.

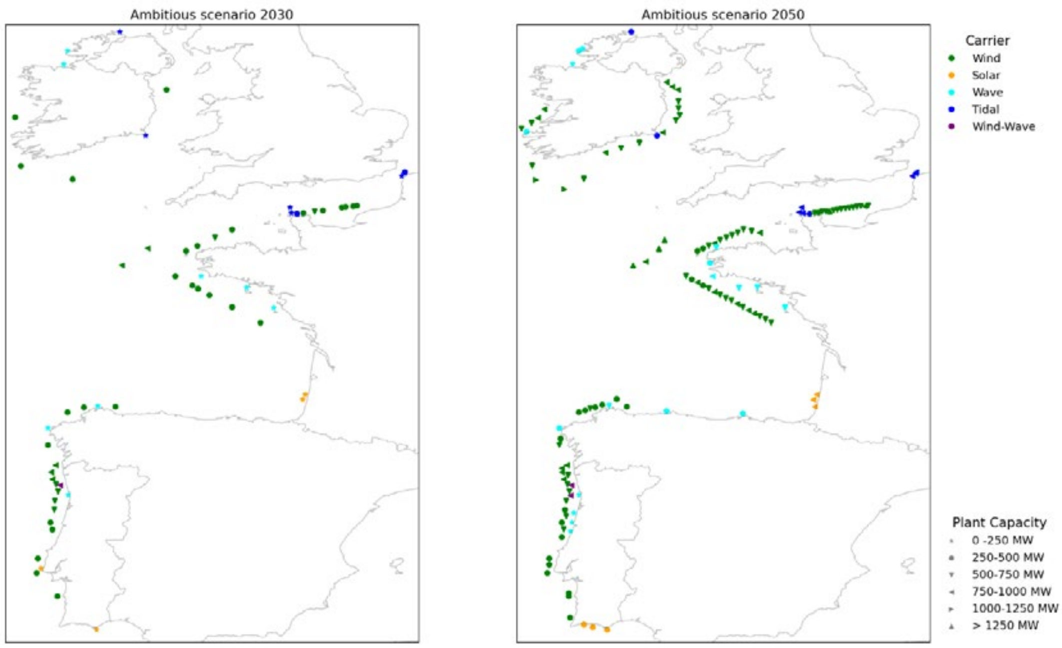

FIGURE 50 : 2030-2050 AMBITIOUS OFFSHORE PRODUCTION SCENARIO FOR THE ATLANTIC REGION

2.4.3. Other main assumptions

The production scenarios include all renewable and non-renewable technologies for the Atlantic countries. The current pathway and ambitious scenario only differ with regards to offshore installed capacity, and they share the same assumptions regarding electricity demand and deployment of onshore technologies, which are aligned with explicit targets in National Energy Plan or relevant long-term strategic documents.

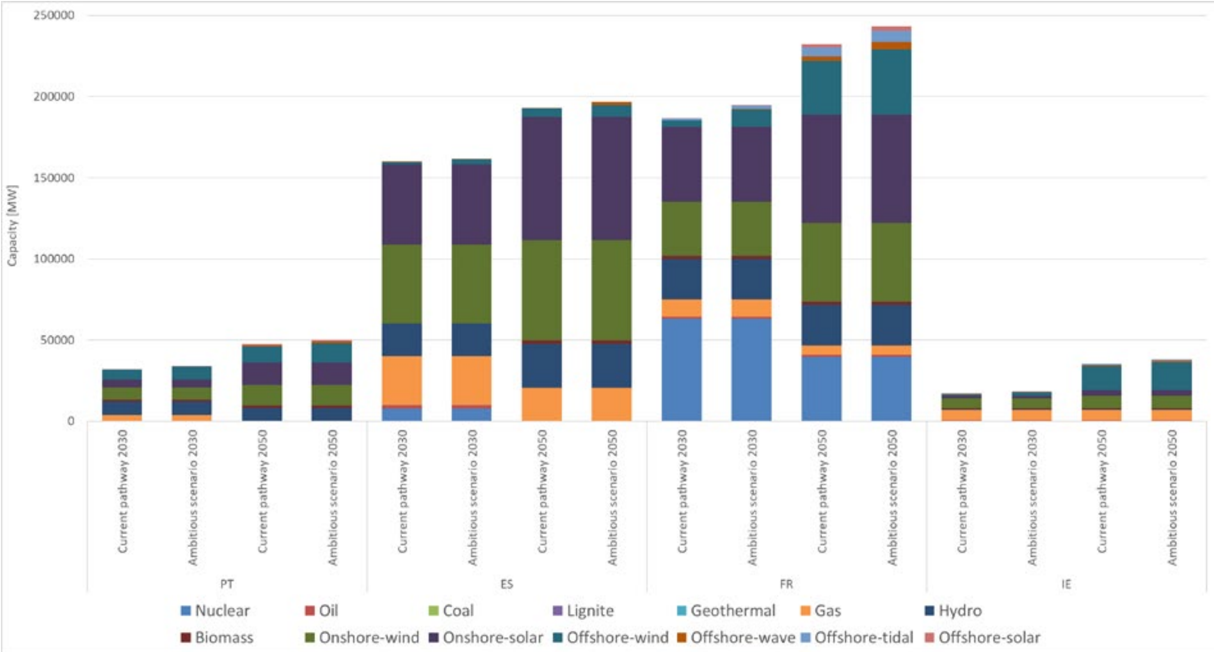

FIGURE 51: CAPACITY ASSUMPTIONS IN THE DIFFERENT PRODUCTION SCENARIOS FOR THE ATLANTIC MEMBER STATES

Overall capacity considers targets concerning the share of renewables in electricity consumption, explicit target of installed RES capacity, targets concerning phase out of existing nuclear or fossil generation technologies. Figure 51 shows the assumed production capacities for the scenarios in exam.

Electricity demand is another key parameter for the power market modelling and power flow analysis. Due to electrification in transport, heating and industry sectors, European electricity demand is expected to increase significantly by 2050. In this study, electricity demand assumptions are based on the national trends' scenario of the (TYNDP 2022 - Scenario report, s.d.), which aims to reflect the commitment of each Member State in meeting the targets set by the EC and National Plans. The variation of electricity demand in 2030 and 2050 is shown in Figure 52, relative to the demand in 2020. For the EU Atlantic Member States, the total electricity demand is assumed to increase by 2% in 2030 and by 41% in 2050.

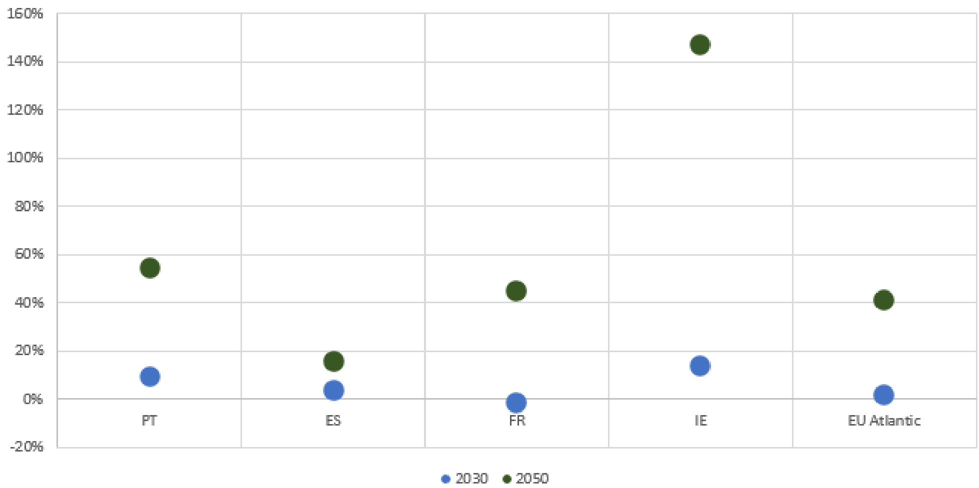

FIGURE 52: ELECTRICITY DEMAND VARIATION RELATIVE TO 2020

Fuel and carbon prices are key parameters for determining the merit order of power generation. In this study, fuel prices are based on the assumptions of the TYNDP scenario report 2020. CO_2 prices are based on the "*Study on the offshore grid potential in the Mediterranean region*". Table 2- provides an overview of fuel assumptions of this study and a comparison with assumptions used in other ENTSO-E, EU and IEA[53] scenarios.

TABLE 2- : FUEL PRICE ASSUMPTIONS USED IN THE STUDY COMPARED WITH OTHER ENTSO-E, EU, AND IEA SCENARIOS

Fuel	Atlantic Study (€/MWh)		Med Study (€/MWh)		TYNDP 2020 (€/MWh)		EU LTS scenarios (€/MWh)		IEA Stated policies (€/MWh)	
	2030	2050	2030	2050	2030	2040	2030	2050	2030	2050
Hard Coal	15.5	24.9	15.5	24.9	15.5	24.9	13.7	15.5	9.7	9.9
Natural Gas	24.9	26.3	24.9	26.3	24.9	26.3	37.2	46.5	24.3	27.0
Light Oil	73.8	79.9	73.8	79.9	73.8	79.9	80.6	95.6	57.2	66.7
Heavy Oil	52.6	61.9	52.6	61.9	52.6	61.9	50.4	60.0	35.6	41.7
Nuclear	1.7	1.7	1.7	1.7	1.7	1.7	-	-	-	-
Lignite	4.0	4.0	4.0	4.0	4.0	4.0	-	-	-	-
CO2 (€/ton)	28	250	28	250	27-53	75-100	28	250- 350	33	43

[53] International Energy Agency

3. GRID OPTIONS

Building on the work of the previous tasks, this section defines options for grid connection for the scenarios outlined in Task 2. Thus, Task 3 suggests ways to connect the identified production blocks to the transmission grid onshore, and, if deemed suitable, to each other.

3.1. Cost information

As with previous studies of regional-scale offshore transmission for the North Sea (Publications Office of the European Union, 2014) and the Mediterranean (Publications Office of the European Union, 2020), the main source of information is ENTSO-E's report on offshore transmission technology (European Network of Transmission Systems Operators for Electricity, 2011). The information and methods described in these three reports are complemented by a survey of recent literature and the consortium's own data and analysis, principally in order to reflect:

- Recent evolution in technology and cost trends since these publications
- Floating technology for offshore platforms and cables
- Cost impacts of the European Atlantic marine meteorology and geotechnical conditions

The main challenges in providing reliable estimates of offshore transmission costs are that

- published data on costs, particularly HVDC equipment, is limited
- important uncertainty on cost-reductions remains, particularly for HVDC equipment
- there is not yet a clear winner in several key technologies, such as converters and floater types

These uncertainties are likely to be significantly reduced in the coming years with new projects, ongoing R&D, and synthesis projects such as the new DNV GL Joint Industry Project on floating offshore substations (Dippel, 2022).

3.1.1. Specificities of the Atlantic Arc areas for offshore power transmission

A brief review of the method and challenges in updating information on offshore infrastructure costs for the study area is provided herein.

Available information on HV equipment costs

The required information on latest technology and cost trends comprises technologies for substations and their components, cables, and marine operations. To date, the best published information on offshore substation costs arguably still are those provided by the ENTSO-E in 2011 (European Network of Transmission Systems Operators for Electricity, 2011). Cost data with such first-hand industry knowledge has not been published since. But some of these costs are likely to be obsolete. While AC substations and components are mature technologies, HVDC offshore transmission is far more recent, so important cost reductions are expected to have occurred since 2011 and to be delivered in the coming years from R&D on converters, circuit breakers and on increasing ratings for components and cables.

There has since been extensive work on offshore grid planning, such as that reported for Great Britain (DNV GL, 2020). Unfortunately, the actual cost data is deliberately removed from the public version of that otherwise extensive report. Nonetheless, (DNV GL, 2020) does provide projections on *relative* cost reductions through to 2050, which will be highly valuable for this study.

A 2019 position paper by WindEurope (WindEurope, 2019b) reports valuable data on offshore wind farm transmission, including CAPEX. Although it does not provide the breakdown between cables and offshore substation, it allows valuable checks of consistency for our estimates. Other industry reports that are used in this study include (Mid-continent Independent System Operator, 2019), which provides up-to-date, extensive and highly detailed cost estimates for onshore electricity transmission components in the United States, as useful benchmarks for this study.

The academic literature is used to complete these. One limitation is that these publications in their great majority have focussed on the North Sea rather than the European Atlantic. Also, academic literature typically does not focus on precise costs, and typically has less access to such data than industry reports.

Available information on cable costs

Compared to offshore substation and their equipment, for subsea cables it is relatively easier to provide reliable estimates of current costs and expected cost reductions. Cables being generally a less complex and more mature technology than offshore substations, there are less uncertainties on future costs. The cost breakdown is simpler for cables, dominated by the cable supply and its installation, whereas substations have many more components and many different technologies can be used. This results in more reliable estimates from available lump sum contract data for e.g. wind farm export cables.

One decisive factor that is hard to predict is the R&D and its impact on increase in power ratings. This is further complicated by the nature of the market for subsea cables, which has not been a perfect competition between suppliers, according to e.g., (European Commission, 2014).

Cost of floating substation vs. bottom-fixed substations

The cost impact of floating technology is another important difference with the North Sea. These include:

- cost of floater for the substation,
- additional requirements for HV equipment, such as fatigue cycles for inertial loads,
- dynamic instead of static subsea cables,
- impacts on offshore installation and maintenance operations.

Unlike the North Sea where jackets, gravity-base or even power link islands are used or planned for offshore substations, cost estimations for offshore grid in the European Atlantic require consideration of floating substations. The threshold depth for floating systems is an important consideration for this study. DNVGL estimates that bottom-fixed systems may be competitive to 100 m (DNV GL, 2022b) with current technology. Thus, it is likely that at least a few gigawatts of bottom-fixed offshore wind in France will use bottom-fixed substation, including possibly some of the farms with floating wind turbines. This depth limit may also be pushed further, depending on technology improvements.

At any rate, scenarios where offshore energy deployment in the European Atlantic are of a scale that require consideration of an offshore grid must include floating offshore substation deployments. Foundation cost is an important part of overall substation costs, so offshore grid planning in this region requires some estimates of their cost.

Providing reliable predictions for substation floaters is not easier than for turbine floaters. The main uncertainty is the lack of a clear winner between very different existing types of floaters (semi-submersible, spar, barge, tension legs…) and others being investigated. Research on floaters for offshore substations has been less active than that for floaters for wind turbines. In comparison to floating wind turbines, of which there are already many operating, the only open-sea deployment to date is the 25 MW floating substation off Fukushima, Japan.

FIGURE 53 : THE 25 MW, 66 KV FUKUSHIMA FLOATING OFFSHORE SUBSTATION (IMAGE: FUKUSHIMA FORWARD CONSORTIUM)

In general, it is expected that floating foundation for offshore substations will result in overall increase in costs compared to bottom-fixed systems. Preliminary results in our analysis would suggest a 50-150% increase in the foundation cost, though this may be somewhat offset by potentially lower installation costs. It is worth mentioning that according to preliminary sizing for semi-submersibles, the floater for the substation may not be substantially costlier than the floaters for turbines larger than 15 MW. This is because although substations are much heavier than turbines, their overturning moment will be considerably less, and floater sizing is typically governed by the latter rather than turbine weight. Mooring systems are likely to be more expensive for floating substations than for floating turbines, because of the need to accommodate multiple power cables and reduce platform excursion to protect these cables from excessive bending, tension, and premature fatigue failure. The technology otherwise being quite similar, the important reductions in floater costs, which may be a pre-requisite for gigawatt-scale deployments in the European Atlantic, may also deliver significant cost-reduction for substations' floaters.

As in the case of turbine floaters, there are uncertainties on the type of stabilisation mechanisms that will be most competitive for substations floaters. Several projects are considering semi-submersible floaters, but there are also advanced analysis for barges. The Fukushima floating substation is ballast-stabilised (a modified spar-type of floater). With their reduced horizontal excursions, mooring-stabilised floaters such as tension leg platforms may have advantages in terms for length requirements and fatigue of dynamic cables and connectors, but the technology is less mature.

Impact of floating motion on HV equipment costs

The cost impact of new design requirements for converters and breakers for floating applications is being assessed by various specialist teams. This is an area of active research so also will introduce uncertainty in our cost estimates.

Currently available static platform HV equipment must anyways be designed to comply with some amount of seismic loads, as well as installation and transport loads. These may impart inertial loads of the same orders as those resulting from wave motion in a floating substation.

The main uncertainty regarding floating applications may not be so much in the magnitude of inertial loads, but rather on the impact of much higher number of load cycles, typically a million a year if dominated by wave frequency. (There could one or two orders of magnitude less cycles if fatigue loads are dominated by mooring system resonance). This large number of load cycles will require particular attention to stress concentration, especially at interfaces and bends in the stress flow. The fatigue impact on airtightness of gas insulated switchgear tanks must be assessed and certified.

Floating application may also result in larger amplitude motions, and at different periods, than for bottom-fixed platforms, which could result in sloshing excitation in e.g. transformers oil tanks. Testing for fatigue and certification will require funds and time, and may even result in requirements for new designs.

Dynamic cable cost impacts

Dynamic cables are likely to be required near the offshore substation. Consortium experience is that dynamic cables are typically 15-20% more expensive than static subsea cables of the same rating. However, at the moment dynamic cables are only available up to 66 kV. The higher voltage required for offshore transmission will require new developments, that introduce uncertainty on cost estimates for this study.

On the other hand, it is likely that only a small portion of the subsea cable for offshore transmission will need to be dynamic. This is different for cabling within an offshore farm, where some preliminary designs consider that most or all of the intra-farm cable will be dynamic - but this doesn’t affect power transmission downstream of the substation or the design of an offshore grid. The connection of the dynamic cable to a static cable on the seabed will require an additional interface. Asymmetric factory joints of this type currently would cost these at some 200 k€ per joint according to our data. These are for joints of 66 kV cables with asymmetry in the copper section. Between dynamic and static cables the asymmetry will include significant differences in armouring, and costs may be significantly higher for higher voltage cables.

Nonetheless, considering the length of cable required for an offshore grid, only a very small portion of the total for an offshore grid will need to be dynamic. Cost impacts are expected to be small once the technology is developed for high voltage dynamic cables and their joints to static cables.

Weather and seabed difference impacts on costs

Finally, installation operations are a significant part of the total cost, both for offshore substations and subsea cables. The marine meteorology and geotechnical difference of the Atlantic region with the North Sea must thus be considered. In general, waves are stronger in the Atlantic than in the North Sea or Mediterranean. Winds are less in the southern part of the European Atlantic than in the North Sea, but are about as strong in the West of Ireland. This will significantly impact marine logistics and operations, and particularly weather windows for heavy lift operation from floating vessel to floating platform.

However, installation cost may depend even more critically on the floater technology than on the marine conditions. For semi-submersible and barges, it is likely that the substation topside will be installed at a port or in a sheltered area, before being towed on the floater to its final location. Installation of substation topside on ballast-stabilised spar may be done offshore or in a sheltered area of sufficient depth. In this case, installation may be cheaper than for bottom-fixed substations. On the other hand, installation on a mooring-stabilised floater such as tension leg platform would probably require offshore heavy lift between two floating bodies, which is likely to make installation significantly more expensive than for bottom-fixed substations.

FIGURE 54 : INSTALLATION OF THE 2100 TONS TOPSIDE OF THE ST NAZAIRE WIND FARM (SOURCE: ADEME)

For cable installation, winds, waves and current reduce the operating window for the laying operation, thus increasing vessel costs. Cable burial cost will strongly depend on the seabed nature. Current trenchers may burry a few meters per minute in soft sediment, but in rocky bottom this can easily be ten times longer and costly. In general, the European Atlantic has less areas of soft seabed than the North Sea. Trenching time will strongly impact costs if the cable laying vessel is used to support the trenching operation (typically in simultaneous laying and trenching), but significantly less if post-lay burial is chosen – but this entails additional risks to the cable.

3.1.2. Costs used in the study

The costs used for evaluating grid options are mainly based on those used for similar studies in the North Sea and the Mediterranean. Where possible this information is complemented with project data from the consortium. As is clear from the previous section, a generic cost for cables or substations in the region necessarily entails important simplifications, and is subject to uncertainties from expected technology development in HV equipment and floating platforms.

3.1.2.1 Costs for AC offshore substations

For the purpose of evaluating grid options, while keeping complexity manageable, capital expenditure for offshore AC substations are provided in euros per watt. The main information source is from the North Sea study. The Mediterranean Study's costs are in the same range. Both appear lower than information available for specific projects (all at 220 kV), such as Danish wind farms Anholt, Horns Rev- 3 and Kriegers Flak's two substations (ENERGINET , 2017). The United Kingdom's ORE Catapult provides itemized costs that can be used to evaluate costs for a 220 kV substation. These also appear to result in substantially higher costs than those obtained from ENTSO-E (ENTSO-E, n.d.) and the previous studies for the Northern Sea regions (European Commission , 2014) and Mediterranean (European Commission , 2020). These comparisons are however difficult because of the lack of publicly available detailed cost breakdown on existing projects.

In order to provide generic costs for the region, and for various power ratings the number of switchgears is assumed to be roughly proportional to the power rating of the substation. Likewise for reactive power compensation per kilometre. Jackets and gravity-base costs provided in the North Sea study are replaced with a cost estimated for a semi-submersible floater, estimated from the consortium's projects database. Resulting costs for various power ratings and two voltage ratings are summarized in the table below. The distance to shore, here of 200 km, is an adjustable parameter for the various scenarios explored.

TABLE 3: COSTS OF AC OFFSHORE SUBSTATIONS

			220 kV OSS power rating, MW				400 kV OSS power rating, MW			
			500	850	1250	2000	500	850	1250	2000
Substation electrical equipement										
220 kV switchgear	2.68	unit	2.68	5.36	10.72	21.44				
400 kV switchgear	4.545	unit					4.545	9.09	18.18	36.36
Transformation	10 000	€/MVA	5	8.5	12.5	20	5	8.5	12.5	20
Reactive compensation	63 250	€/MVAr	12.7	25.3	50.6	101.2	12.7	25.3	50.6	101.2
dist. to shore	200	km								
Substation floater and installation		M€								
topside			21	26.5	26.5	32	21	26.5	26.5	32
floater			20	23	26	30	20	23	26	30
install			5	7	8	10	5.5	7.7	8.8	11
total OSS supply & install		M€	66.3	95.7	134.3	214.6	68.7	100.1	142.6	230.6
OSS cost €/W		**€/W**	**0.13**	**0.11**	**0.11**	**0.11**	**0.14**	**0.12**	**0.11**	**0.12**
Total platform + install		M€	46.00	56.50	60.50	72.00	46.50	57.20	61.30	73.00

3.1.2.2 Costs of DC offshore substations

As for AC substation, the main information sources are from ENTSO-E and the Northern Seas regions and Mediterranean studies. This is complemented by limited available public information on existing DC infrastructure offshore, such as the Dolwin projects. Wind Europe's report on the development of offshore grids (Wind Europe, 2019) provides valuable information on lump sum costs of offshore DC projects. Valuable public information is also available on certain DC interconnectors, such as NordLink. These normally do not have some of the components of offshore energy substations (such as array cable links), but costs of some of the main components such as VSC HVDC converter stations should be similar.

In general, the costs estimated based on the previous studies by ENTSO-E, for the Northern Seas and for the Mediterranean regions tend to be on the lower end of those obtained from limited public information on existing HVDC stations such as the Dolwin platforms. However, they tend to concur with estimates based on public information on HVDC interconnectors.

For the purpose of evaluating HVDC grid options in the Atlantic Arc, the costs in the following table are used. Floater costs are based on the consortium projects' data.

TABLE 3-3: COSTS OF DC OFFSHORE SUBSTATIONS

Voltage	kV	300	320	500	500
Power rating	MW	500	850	1250	2000
HVDC station VSC	M€	92	105	150	196
Platform cost	M€				
Floater		25	28	30	32
Topside		38	38	65	65
Installation		10	11	15	18
Total DC OSS	M€	165	182	260	311
Total DC OSS €/W	**€/W**	**0.330**	**0.214**	**0.208**	**0.156**
Platform total	M€	73	77	110	115
Platform total	€/W	0.15	0.09	0.09	0.06

3.1.2.3 Costs of AC power cables

For the purpose of grid options estimation, a generic cost per meter and rated power is estimated for the Atlantic Arc. As for other inputs to the cost model for grid options, this requires considerable simplification.

For 220 kV cables, costs from the consortium project database are used. These are usually in line with published costs for most offshore wind farms, though certain projects have published lower costs, usually in more favourable seabed conditions. Costs obtained from the Mediterranean and northern seas regions studies are similar or slightly lower. Costs provided for UK wind farms by ORE Catapult (ORE Catapult, n.d.) are significantly higher. For other voltage, there are much fewer public data available and costs from the Northern Sea and Mediterranean regions studies are used.

Resulting generic costs for AC power cables are shown in the two tables below, for 220 kV and other voltages, respectively.

TABLE 3-4: COSTS OF 220 KV AC OFFSHORE CABLES

	total mm2	voltage kV	capacity A	pow er MW	upply co: €/m	upply co: €/MW/m	supply & install €/m	supply & install €/MW/m
AC offshore cable								
Triphasic, 220 kV, copper	**630**	220	**756**	**288**	724	**2.51**	**1 024**	3.55
Triphasic, 220 kV, copper	**800**	220	**960**	**366**	823	**2.25**	**1 123**	3.07
Triphasic, 220 kV, copper	**1000**	220	**1200**	**457**	928	**2.03**	**1 228**	2.68
Triphasic, 220 kV, copper	**1200**	220	**1440**	**549**	1062	**1.94**	**1 362**	2.48
Triphasic, 220 kV, copper	**1600**	220	**1920**	**732**	1289	**1.76**	**1 589**	2.17

TABLE 3-5: AC CABLE COSTS, VARIOUS VOLTAGES

Cable capacity, copper 1.2 A/mm2
Cable capacity, aluminum 1.0 A/mm2

	total mm2	voltage	capacity A	**Power MW**	supply cost €/m	supply cost €/MW/m	supply & install €/m	**supply & install €/MW/m**
1x3x400mm² cu 220kV Offshore	400	220	480	**183**	540	2.95	940	**5.14**
1x3x1600mm² alu 220 kV Offshore	1600	220	1600	**610**	875	1.44	1 275	**2.09**
2x3x1600mm² alu 220 kV Offshore	3200	220	3200	**1219**	1 750	1.44	2 150	**1.76**
3x3x1600mm² alu 220 kV Offshore	4800	220	4800	**1829**	2 625	1.44	3 025	**1.65**
3x1x1200mm² alu 220 kV Onshore	1200	220	1200	**264**	525	1.99	675	**2.56**
3x1x1400mm² alu 220 kV Onshore	1400	220	1400	**308**	550	1.79	700	**2.27**
3x1x2000mm² alu 220 kV Onshore	2000	220	2000	**440**	625	1.42	775	**1.76**
6x1x1200mm² alu 220 kV Onshore	2400	220	2400	**528**	1 050	1.99	1 200	**2.27**
6x1x1400mm² alu 220 kV Onshore	2800	220	2800	**616**	1 100	1.79	1 250	**2.03**
6x1x2000mm² alu 220 kV Onshore	4000	220	4000	**880**	1 250	1.42	1 400	**1.59**
9x1x1400mm² alu 220 kV Onshore	4200	220	4200	**924**	1 650	1.79	1 800	**1.95**
9x1x2000mm² alu 220 kV Onshore	6000	220	6000	**1320**	1 875	1.42	2 025	**1.53**

offshore cable installation 400 €/m
onshore cable installation 150 €/m

3.1.2.4 Costs for DC power cables

For DC power cables, the generic cost for the purpose of grid options evaluation is based on previous studies for the Northern Sea and Mediterranean regions. These appear to be slightly higher than costs that may be estimated based on public information on existing DC interconnectors. However, they are significantly lower than those that may be estimated from public information on projected costs for planned interconnectors (costs may have increased significantly in the last few months).

The costs used are summarized in the table below.

TABLE 3-6: DC POWER CABLE COSTS

Cable capacity, copper 1.2 A/mm2
Cable capacity, aluminum 1.0 A/mm2

	total section mm2	voltage	capacity A	**power MW**	supply cost €/m	supply cost €/MW/km	supply & install €/m	**supply & install €/MW/km**
2x1x300mm² cu ±320 kV DC Offshore	300	320	360	**115**	600	5.21	1 000	**8.68**
2x1x1000mm² cu ±320 kV DC Offshore	1000	320	1200	**384**	1000	2.60	1 400	**3.65**
2x1x2500mm² cu ±320 kV Offshore	2500	320	3000	**960**	1324	1.38	1 724	**1.80**
2x1x1500mm² cu ±500 kV Offshore	1500	500	1800	**900**	1120	1.24	1 520	**1.69**
2x1x2500mm² cu ±500 kV Offshore	2500	500	3000	**1500**	1468	0.98	1 868	**1.25**
2x1x500mm² alu ±320 kV Onshore	500	320	500	**160**	546	3.41	696	**4.35**
2x1x2400mm² alu ±320 kV Onshore	2400	320	2400	**768**	750	0.98	750	**0.98**
2x1x1500mm2 alu ±500 kV Onshore	1500	500	1500	**750**	858	1.14	1 008	**1.34**
2x1x2500mm2 alu ±500 kV Onshore	2500	500	2500	**1250**	1000	0.80	1 000	**0.80**

offshore cable installation 400 €/m
onshore cable installation 150 €/m

3.2. Method

The grid connection is made in two steps. First, a base alternative is calculated. The base alternative is a radial connection between each ORE plant and the nearest onshore transmission grid station located in the same country as the ORE plant. Locations of onshore substation have been retrieved from the ENTSO-E grid map[54] and further updated through other maps or studies whereever possible. The connection, whether HVAC or HVDC, is designed and dimensioned based on the installed power of the ORE plant and its distance from the transmission substation. The radial connection does not have full redundancy, meaning that the failure of a component might lead to the loss of an entire ORE plant. Nevertheless, in case of parallel cables, failure of a cable might mean that the remaining cables can still transmit part of the production from the ORE plant. On the other hand, failure of one component will not lead to the loss of production from more than one ORE plant.

In a second step, the specific conditions of each ORE plants are evaluated, and one or more interconnections are considered, if deemed advantageous. eseThese interconnections can include grouping several ORE plants, connecting it to more than one onshore station, or to other ORE plants so that two countries become interconnected. Unlike the radial topology, the hybrid one is more reliable since it ensures a certain redundancy in the transmission: the power from an ORE plant can be delivered through multiple lines, thus if a line fails the other(s) can be used to deliver the energy. A consequence of this configuration is its higher cost since it requires a bigger initial investment in absolute figures, although it is important to note that, where a hybrid project is identified as providing positive socio-economic benefits, such costs would be shared between the involved Member States, and as such typically lower than those of the radial project. Therefore, investment in a hybrid grid would pay for itself through strategic benefits enabled through a coordinated network development (i.e. energy trading between EU Member States, enhanced security of supply, etc.) and sharing of costs. A hybrid offshore transmission project interconnecting Member States with offshore wind farms will be sensible where the social welfare generated by the interconnection exceeds the additional investment costs of a longer line. Moreover, a coordinated grid planning approach based on hybrid projects will have lower overall environmental impacts compared to an uncoordinated radial approach.

[54] https://www.entsoe.eu/data/map/

Within this study two different grid layouts, *radial* and *hybrid*, are considered and benchmarked via Cost Benefit Analysis (CBA), expected for Task 3. The methodology for the definition of the grid options and for the CBA are explained in Section 3.2.2.

3.2.1. Assumptions

3.2.1.1 Assumptions for the radial configuration

The radial case is considered as the starting point, upon which the hybrid configuration can be built.
The following assumptions are made for the definition of the radial case:

- Each ORE is connected to substations in the same country.
- For each ORE project, the appropriate onshore substation is chosen based on the closest distance and hosting capacity. Despite a lack of hosting capacity, substations might be selected if there is no better alternative nearby. In this case, the cost to upgrade the substation to satisfy the ORE capacity is computed and included in the total operational cost.
- The length of the export cable from the ORE project to the onshore substation includes deviations around constrained areas and water depth. Offshore and onshore cables' length and cost are calculated separately. No overhead lines are considered.
- Each connection is optimally dimensioned to accommodate the maximum power of the ORE plant.

The best technology, either HVAC or HVDC, is chosen by solving the optimization problem. It is affected by cable length and total cost (CAPEX, OPEX and losses) over the optimization time horizon (25 years).

3.2.1.2 Assumptions for the hybrid configuration

Thehybrid case is defined upon the radial configuration. The following assumptions are made for the definition of this scenario:

- All ORE plants connected to the same station are grouped together, and the connecting distance was assumed to be equal to the average distance from the included ORE plants to the station.
- Each hub is connected to a substation in their same country. The appropriate onshore substation is chosen, based on the closest distance and hosting capacity. Despite a lack of hosting capacity, substations might be selected if there is no better alternative nearby. In this case, the cost to upgrade the substation so that it satisfies the ORE hub capacity is computed and included in the total operational cost. This approach is detailed in Section 3.2.2.
- The associated costs and losses for the connection are calculated by using the total installed power of the ORE cluster and its distance from shore.
- The length of the export cable from the ORE cluster to the onshore substation includes deviations around constrained areas and water depth. Offshore and onshore cables' length are calculated separately and so their cost. No overhead lines are considered.
- Each connection is optimally dimensioned so to accommodate the maximum power of the ORE cluster as explained in Section 3.2.2

- The best technology, either HVAC or HVDC, is chosen by solving the optimisation problem. It is affected by cable length and total cost (CAPEX, OPEX and losses) over the optimisation time horizon (25 years).

The following considerations are examined when determining whether there are advantages in offshore interconnections:

- Identification of radial clusters: Are there any obvious benefits from connecting an ORE plant or an ORE cluster to more than one station in the same country (i.e. increased penetration in the energy mix, reduction of GHG emissions and/or reduction of the overall cost)?
- Identification of hybrid projects: Are there any ways to connect ORE clusters belonging to different Member States, thereby forming a link between the countries (i.e. increased penetration in the energy mix, reduction of GHG emissions and/or increasing overall social welfare)?
- Are there any planned or ongoing interconnection projects in the vicinity of the ORE clusters so that there might be coordination benefits if an optional grid connection is used?

3.2.2. Grid planning methodology

The grid-planning methodology proposed in this study starts with the representation of the future electrical system and it culminates with the generation of optimized grid configurations for the scenarios defined in Task 2. Once the grid configurations are defined, energy market and energy dispatch simulations are performed to assess different metrics such as ORE penetration in the energy mix, ORE curtailment, energy losses and CO_2 emissions, necessary for the benchmark of the different options as described in Section 3.2.2.4.

3.2.2.1 Electrical system representation

The energy system representation is the first key step of the overall methodology. It articulates over three phases implemented into EDP NEW's grid planning tool that works with oopen-source data. The tool acts as both grid-optimization tool and dispatch simulator and its operation are described in the following sections.

Grid modelling

Starting from the current transmission network (encompassing nodes, power lines and substations) provided by ENTSO-E grid map[55], the grid of 2030 and 2050 are modelled considering the extension planned for the onshore transmission network as per ENTSO-E TYNDP[56] (10-years network development plan) 2030-2040 (see Figure 55). Interconnectors are also accounted for.

[55] https://www.entsoe.eu/data/map/ https://www.entsoe.eu/data/map/
[56] https://tyndp2020-project-platform.azurewebsites.net/projectsheets/transmission https://tyndp2020-project-platform.azurewebsites.net/projectsheets/transmission

FIGURE 55: PLANNED TRANSMISSION PROJECTS IN OR AROUND THE ATLANTIC ARC

Generation modelling

Generation is represented at node level, considering the power plants' electrical substations. Distinction is made between different generation technologies (i.e. PV, wind, hydro, nuclear, natural gas-fired, etc.) to consider their technical and economic characteristics. Typical parameters integrated in the computation are: efficiency, ramping rates, availability (particularly important for renewable energy sources), technical minimum, etc. For this purpose, a power plant database for both conventional and renewable generation units in the countries at issue (France, Ireland, Spain and Portugal) isis created containing the abovementioned information, complemented by their location in terms of latitude and longitude (particularly important to identify substation connection points and moreover, for renewables, to retrieve their hourly availability). This database considers the current power plant portfolio of the different countries and the planned future projects and national policies (see Task 2). Different open-source databases were analysed:

- *Open Power System Data*[57], for conventional power plants in Spain and France;
- *Global Power Plant Database* - Global Energy Observatory, for both conventional and renewable power plants in all the four countries;
- *ENTSO-E PPL Transparency Platform*[58] – for conventional power plants in all the countries;
- *e2p - endogenous energies of Portugal*[59] – for both conventional and renewable power plants in Portugal;
- *AEE- Asociacion Empresarial Eolica*[60] – for wind farms in Spain;

[57] *Open Power System Data*. 2020. Data Package Conventional power plants. Version 2020-10-01 https://datasets.wri.org/dataset/globalpowerplantdatabase
[58] https://transparency.entsoe.eu/generation/r2/installedCapacityPerProductionUnit/show
[59] https://e2p.inegi.up.pt/
[60] https://aeeolica.org/sobre-la-eolica/mapa-de-parques-eolicos/#/

- *Eirgrid – "All-island Generation Capacity Statement 2021-2030"*[61] – for dispatchable generation units in Ireland;
- *OpenStreetMap*[62] *and OpenInfrastructureMap*[63] - for all types of power plants in the four countries.

Load modelling

The electrical demand determines the need for system balancing and use of resources. In particular, the spatial distribution of the load defines the need for transmission, as power may be generated far from the consumption centers. The ENTSO-E website[64] provides hour by hour data of the aggregated demand in each country. However, the current application (dispatch simulator) requires data at the resolution of the network model. This makes it necessary to disaggregate the load signal, i.e., to split the country-aggregated demand into demand's components at node level.

The load disaggregation is an impossible task to achieve precisely, therefore a heuristic approach is proposed. For this study, it is reasonable to compute the different load projections according to the demography and/or economic data: the higher the population of a certain area and the level of industrialization, the higher we would expect the electricity demand of that area to be (Jensen, T. V. & Pinson, P., 2017).

With this approach, the load can be represented per node as for the generation units.

The first step to the load disaggregation is to estimate each county hourly demand for 2030 and 2050. This is achieved by identifying "typical demand pattern" upon historical dataset from the ENTSO-E database and applying it to each country's 2030 and 2050 electricity consumption forecast (see Task 2).

Secondly, by means of a top-down approach, the demand is disaggregated for each node considering the Gross Domestic Product (GDP) and the Population Density (PD) of the node's region.

The countries are partitioned into Voronoi cells as catchment areas (Figure 56), each of which is assumed to be connected to the substation by lower voltage network layers (MV or LV). These Voronoi cells are used to compute the share of demand drawn at the substation. Figure 56 shows the partition of one country into Voronoi cells:red dots represent the electrical substation where the load is accounted for. These substations are the ones connected to lower voltage network layers, meaning that they are connected to MV or LV networks.

[61] Appendix 2, https://www.eirgridgroup.com/site-files/library/EirGrid/208281-All-Island-Generation-Capacity-Statement-LR13A.pdf
[62] https://www.openstreetmap.org/#map=4/47.75/-2.02
[63] https://openinframap.org/#2/26/12
[64] ENTSO-E European Network of Transmission System Operators for Electricity. www.entsoe.eu.

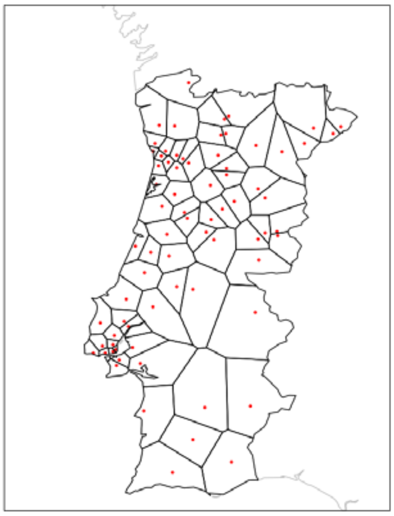

FIGURE 56: COUNTRY SUBDIVISION IN VORONOI CELLS: RED DOTS ARE THE SUBSTATION TO WHICH THE LOAD WILL BE "ATTACHED".

The aggregated load time-series is distributed to the substations in each country with 60% according to the gross domestic product (GDP), as a proxy for industrial demand, and the remaining 40% as the residential demand according to population within a Voronoi cell (Jonas Hörsch, Fabian Hofmann, David Schlachtberger, Tom Brown, 2018). The 60-40% split is based on a linear regression analysis of the per-country data and is consistent with the values used in (J. Egerer, s.d.). The two statistics, GDP and population density, are mapped from the Eurostat Regional Economic Accounts database (nama 10-reg) for NUTS3 regions to the Voronoi cells in proportion to their geographic overlap (see Figure 57). In Figure 57 the areas in blue represent the NUTS3 regions of the country for which GDP[65] and PD[66] are known.

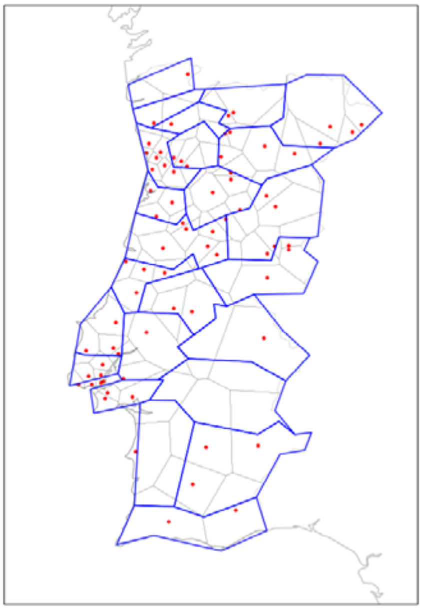

FIGURE 57: NUTS3 REPRESENTATION AND OVERLAP WITH VORONOI CELLS.

[65] https://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do
[66] https://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do

3.2.2.2 Radial layout

The ORE deployment scenarios defined in Task 2 are integrated in the electrical system modelled as explained in the previous sections. As stated before, the radial case represents the basis for the whole analysis, and it articulates over two steps:

- *Counterfactual layout:* it is the basis for the optimization of the radial case. Each ORE plant is individually connected to the most suitable offshore substation, according to its hosting capacity. Onshore grid expansion is not taken into account.
- *Integrated layout:* it represents the optimization of the counterfactual layout. Onshore grid expansions are taken into account in the optimization problem so as to reduce the number of connections. ORE plants are clustered together and then connected to the most suitable onshore substation.

3.2.2.2.1 Counterfactual layout

An optimization process is carried out to determine the best infrastructure (either AC or DC), by minimizing the investment cost encountered to deploy such grid topology. The objective function is as follows:

$$min_{Fl} \sum_{l} c_l . F_l \qquad \textbf{EQUATION 7}$$

EQUATION 7 represents the investment necessary to deploy the ORE projects for the scenario and the grid infrastructure. It includes:

- The branch capacities F_l, expressed in MW;
- The unit cost c_l, expressed in €/MW. The unit cost considers both the cables and offshore substations costs and the costs associated to power losses. These costs are detailed in Section 3.1.2.

EQUATION 7 is subject to some technical constraints:

- Each ORE should be connected to one and just one onshore substation;
- The sum of the ORE plants connected to each substation should not exceed the substation hosting capacity.

3.2.2.2.2 Integrated layout

In the integrated layout, onshore network expansions are considered in the offshore grid planning. The optimization problem is decoupled into three subproblems (Yang Liu, Yang Fu, Ling-ling Huang, Zi-xu Ren, Feng Jia, 2022):

- *Point of common coupling (PCC) optimizer*, whose objective is to optimize the onshore substations capacity (by means of onshore grid expansion) so as to accommodate the whole offshore capacity, while maximizing social welfare as explained in 3.2.2.2.2.1.
- *Offshore substation (OS) optimizer*, whose objective is to find the best location and capacity of the offshore substation that collects different ORE plants.
- *Offshore grid optimizer,* which determines the best connection between onshore substation and offshore substation based on the result of the previous two optimizers.

Figure 58Figure 58: Optimisation framework shows a graphic representation of the three-steps grid optimization.

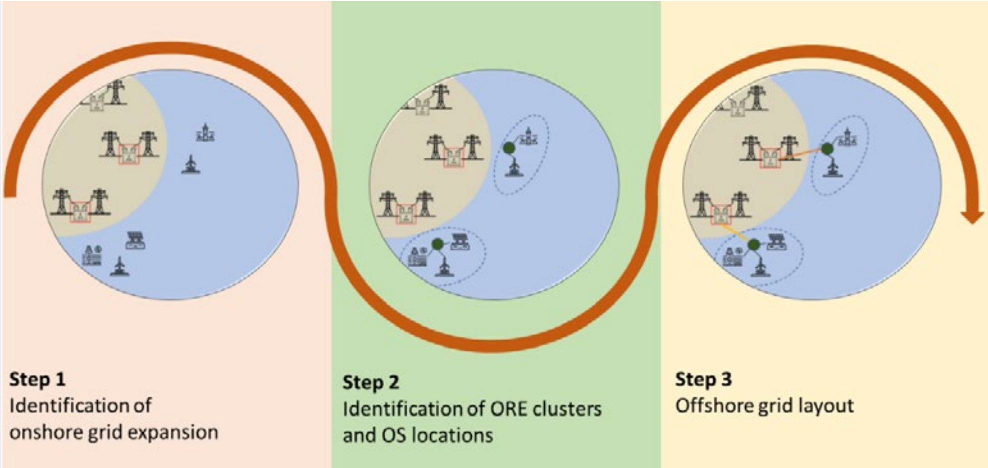

FIGURE 58: OPTIMISATION FRAMEWORK

3.2.2.2.2.1 PCC optimizer

The scope of the PCC optimizer is to consider onshore network expansions so that all the ORE capacity can be connected to onshore substations. The onshore network expansions consider both the cost to upgrade the substations themselves (hence to upgrade their transformers, switchgears, etc.) but also to upgrade the transmission lines connected to them. These onshore grid expansions are set by maximizing the social welfare over a given time span (30 years). This optimization problem considers the grid as modelled and described in Section 3.2.2.1.

The objective function of the PCC optimizer can be written as follows:

$$\max_{P_{expansion_m}, P_{substation_{sub}}} \sum_{y=0}^{29} \left(\sum_{t=1}^{8760} \big(D(t) - S(t)\big) \right) * \frac{1}{(1+a)^y} - \sum_{m=1}^{nl} length_m * Cost\_line_{\frac{MW}{km}} * P_{expansion_m}$$
$$- \sum_{sub=1}^{ns} Cost\_sub_{MW} * P_{substation_{sub}}$$

Where:

- $D(t)$, represents the demand curve;
- $S(t)$, represents the supply curve;
- a, is the discount rate (5%);
- nl, is the set of transmission lines subject to expansion;
- $length_m$, is the length of the m-th line;
- $Cost\_line_{\frac{MW}{km}}$, is the cost to upgrade 1km of line by 1MW (see Table 3-1);
- $P_{expansion_m}$, is the output of the optimisation problem and represents the expansion in MW of the m-th line;
- ns, is the set of substations subject to expansion;
- $Cost\_sub_{MW}$, is the cost to upgrade a substation by 1MW (see Table 3-2);
- $P_{substation_{sub}}$ is the output of the optimisation problem and represents the expansion in MW of the sub-th substation.

Costs for grid expansion, to upgrade transmission network and associated equipment, were retrieved from (Acer, 2015) and are summarized in Table 3-1 and Table 3-2.

TABLE 3-1: TRANSMISSION NETWORK COST

	Type	Total cost per circuit route length (km)	Capacity (MVA)	Cost (€/km*MVA)
Over-head lines	2-circuit, 380-400 kV	1.060.919	1500	707
	1-circuit, 380-400 kV	598.231	750	797
	2-circuit, 220-225 kV	407.521	800	509
	1-circuit, 220-225 kV	288.289	400	720
Underground cable	2-circuit, 380-400 kV	4.905.681	1500	3.270
	2-circuit, 220-225 kV	3.314.047	800	4.142
	1-circuit, 220-225 kV	2.224.630	400	5.561

TABLE 3-2: SUBSTATION COST

Substation total cost per rating (€/MVA)	38.725

With the assumption of inelastic load, the objective function becomes as follows:

$$min_{g_{n,r,t}} \sum_{n,r,t,y} o_{n,r} \cdot g_{n,r,t} \cdot \frac{1}{(1+a)^y} + \sum_{m=1}^{nl} length_m * Cost\_line_{\frac{MW}{km}} * P_{expansion_m} + \sum_{sub=1}^{ns} Cost\_sub_{MW} * P_{substation_{sub}}$$

EQUATION 8

Where:

- $g_{n,r,t}$ is he dispatch generation capacity of the unit at time *t* expressed in MWh (it represents the output of the simulation);
- $o_{n,r}$ is the associated variable cost expressed in €/MWh.

EQUATION 8 is subject to technical constraints. From **EQUATION 9** to **EQUATION 15**, constraints are linked to the power flow analysis. **EQUATION 16** and **EQUATION 17** ensure that the onshore grid expansions are such that all the ORE capacity can be accommodated.

$$\sum_{n,r,t} g_{n,r,t} + \sum_{l} \alpha_{l,n,t} \cdot f_{l,t} = d_{n,t} \qquad \forall n,t$$

EQUATION 9

$$f_{l,t} = F_l \qquad \forall n,t$$

EQUATION 10

$$\tilde{g}_{n,r,t} \cdot G_{n,r} \leq g_{n,r,t} \leq \bar{g}_{n,r,t} \cdot G_{n,r} \qquad \forall n,t$$

EQUATION 11

$$-rd_{n,r} \cdot G_{n,r} \leq \left(g_{n,r,t} - g_{n,r,t-1}\right) \leq ru_{n,r} \cdot G_{n,r} \qquad \forall n,r,t$$

EQUATION 12

$$V_{n\_min} \leq V_{n,t} \leq V_{n\_max} \qquad \forall n, t \qquad \textbf{Equation 13}$$

$$\delta_{n\_min} \leq \delta_{n,t} \leq \delta_{n\_max} \qquad \forall n, t \qquad \textbf{Equation 14}$$

$$P_n = \sum_m (KBK^T)_{nm}\theta_m - \sum_l K_{nl} b_l \theta_l^{shift} \qquad \textbf{Equation 15}$$

$$P_{PCCi} = P_{PCCi\_0} + P_{substation_{sub}} \qquad \forall i \in sub \qquad \textbf{Equation 16}$$

$$\sum_{i=1}^{sub} P_{PCCi} = P_{ORE\_total} \qquad \textbf{Equation 17}$$

The output of the PCC optimizer will be the location and capacity of the onshore grid substation, as well as the cost for onshore grid expansions.

3.2.2.2.2.2 OS optimizer

Through algorithms such as k-mean clustering, the different ORE plant can be clustered together so as to identify the location of the offshore substation that minimizes the cost for connecting the ORE devices (wind turbines, wave, tidal and/or solar generators).
The output of this optimizer will be the location and capacity of the offshore substations for each cluster.

3.2.2.2.2.3 Offshore grid optimizer

Once the onshore substation capacity and the offshore substation location/capacity are defined, the Offshore grid optimizer establishes the most economical connection between the two substations. Cost for reactive power compensation and power losses are considered.
The objective function can be written as follows:

$$\min(C_{cable} + C_{compensation} + C_{loss}) \qquad \textbf{Equation 18}$$

Equation 18 is subject to technical constraints. **Equation 19** ensures that the power connected to each substation does not exceed its capacity, while **Equation 20** ensures that the power of each connection between offshore and onshore substation it is equal to the power of that offshore substation.

$$\sum_{i=j}^{n\_branch\_sub\_i} Pbranch\_j \leq P_{PCCi} \qquad \forall i \in sub \qquad \textbf{Equation 19}$$

$$P_{branch\_j} = P_{OS\_j} \qquad \textbf{Equation 20}$$

3.2.2.3 Hybrid layout

In order to build the hybrid layout, the integrated radial topology is used as a reference. Offshore interconnectors are added to the integrated radial topology, and their capacity is optimized so as to maximize the social welfare, via market/dispatch simulations over a 30 years time spam. The objective function of the optimization problem is as follows, considering inelastic load:

$$min_{g_{n,r,t}} \sum_{n,r,t,y} o_{n,r} \cdot g_{n,r,t} \cdot \frac{1}{(1+a)^y} + \sum_{m=1}^{n\_interconnectors} c_m . F_m$$

EQUATION 21

Where:

- $g_{n,r,t}$ is he dispatch generation capacity of the unit at time t expressed in MWh (it represents the output of the simulation);
- $o_{n,r}$ is the associated variable cost expressed in €/MWh;
- F_m is the interconnector capacity expressed in MW;
- c_m is the unit cost expressed in €/MW.

EQUATION 21 is subject to power flow constraints expressed from **EQUATION 9** to **EQUATION 15**.
The output of the optimization problem will be the capacity of each offshore interconnector.

3.2.2.4 CBA Methodology

Within this study, the CBA methodology is in line with the "2nd ENTSO-E Guideline For Cost Benefit Analysis of Grid Development Projects" (ENTSO-E, 2018).
The CBA is performed via a multi-criteria assessment that relies on Market and Network simulations in order to compute different indicators.

Market simulations are used to calculate the cost optimal dispatch of generation units under the constraint that the demand for electricity is fulfilled in each bidding area and in every modelled time step. Besides the dispatch of generation and demand, market simulations compute the market exchanges between bidding areas and corresponding marginal costs for every time step. Market studies are used to determine the benefits of providing additional transport capacity and enabling a more efficient usage of generation units available in different locations across bidding areas. They take into account several constraints such as flexibility and availability of thermal units, hydro conditions, wind and solar profiles, load profile and outages. They also allow the measurement of savings in generation costs due to the investments in the grid (and/or in storage). Market studies results allow the computation of some of the CBA indicators, such as socio-economic welfare (SEW), CO_2 emissions, RES integration and the adequacy component of security of supply. Market simulations are performed by representing each bidding area with a single node where all demand and generators are aggregated. Only constraints on interconnections between bidding areas are considered. The output of market simulations will be used as an input for defining the generation, consumption and power flows in the grid, allowing load flow calculations to be performed.

Network studies represent the transmission network in a high level of detail and are used to calculate the actual load flows that take place in the network under given generation/load/market exchange. Network studies allow the identification of bottlenecks in the grid corresponding to the power flows resulting from the market exchanges. Network studies results allow the computation of some of the CBA indicators such as: losses and the stability component of the security of supply. Re-dispatch simulations, that are based on network studies, are essential to ensure the proper operation of the grid: dispatch simulations compute the cost of alleviating overloads (taken from network simulations) by adjusting the initial dispatch (taken from market simulations) while maintaining the same power plant specific constraints that were also applied for the market simulations such as minimum up- and down times, ramp rates, must-run obligations, variable costs, etc. Re-dispatch simulations assist in the computation of the CBA indicators (the same as for market simulations).

Both market and network simulations are performed in a similar manner, the only difference is that in the market simulations, each bidding zone is represented by a single node hence all the constraints on their internal grid can be neglected. The mathematical problem underlying both market and dispatch simulations is explained below.

The objective function, in the case of inelastic demand, is as follows:

EQUATION 22

$$min_{g_{n,r,t}} \sum_{n,r,t,y} o_{n,r} \cdot g_{n,r,t} \cdot$$

Where:

- $g_{n,r,t}$ is he dispatch generation capacity of the unit at time t expressed in MWh (it represents the output of the simulation);
- $o_{n,r}$ is the associated variable cost expressed in €/MWh.

EQUATION 22 is subject to some technical constraints. **EQUATION 23** (T. Brown, J. Hörsch, and D. Schlachtberger, 2018) ensures that the inelastic electricity demand ($d_{n,t}$) in each bus *n* must be met at each time *t* by the sum of all the energy of the generation units connected to that bus ($g_{n,r,t}$) plus the flows ($f_{l,t}$) from the branches *l*. The variable $\alpha_{l,n,t}$ is used to consider a positive flow if the energy on that branch is injected into the node or, on the other hand, a negative flow if the energy of that branch is coming out from that node. **EQUATION 23** applies Kirchhoff's Current Law (KCL), which guarantees energy conservation at each node.

EQUATION 23

$$\sum_{n,r,t} g_{n,r,t} + \sum_{l} \alpha_{l,n,t} \cdot f_{l,t} = d_{n,t} \qquad \forall n, t$$

EQUATION 24 (T. Brown, J. Hörsch, and D. Schlachtberger, 2018) ensures that there are no grid congestion events along the transmission lines. It shows that the power flowing in a branch at time *t* cannot exceed the rated capacity of that branch.

EQUATION 24

$$f_{l,t} = F_l \qquad \forall n, t$$

EQUATION 25 (T. Brown, J. Hörsch, and D. Schlachtberger, 2018) ensures that the dispatch of generators $g_{n,r,t}$, at each time *t* does not exceed the generator maximum output, constrained by their capacity $G_{n,r}$ and time-dependent minimum and maximum availabilities ($\tilde{g}_{n,r,t}$ and $\bar{g}_{n,r,t}$ respectively, which represent the minimum and maximum capacity factor at that time). In the case of RES generation these are weather-dependent availabilities and set by the available natural resources (eg. sun and wind), while in the case of conventional power plants, the availability is usually constant and might be imposed by their reserve capacity, market commitment, etc.

EQUATION 25

$$\tilde{g}_{n,r,t} \,.\, G_{n,r} \leq g_{n,r,t} \leq \bar{g}_{n,r,t} \,.\, G_{n,r} \qquad \forall n, t$$

Generators' dispatch might also be limited by ramp down/up constraints ($rd_{n,r}$ and $ru_{n,r}$), expressed as percentages of the rated power $G_{n,r}$ as detailed by **EQUATION 26** (T. Brown, J. Hörsch, and D. Schlachtberger, 2018).

EQUATION 26

$$-rd_{n,r} \,.\, G_{n,r} \leq \left(g_{n,r,t} - g_{n,r,t-1}\right) \leq ru_{n,r} \,.\, G_{n,r} \qquad \forall n, r, t$$

Moreover, in order to ensure the stability of the grid, the voltage level in each node must be kept within a pre-defined interval, as described by **EQUATION 27** (T. Brown, J. Hörsch, and D. Schlachtberger, 2018), where $V_{n,t}$ is the voltage at node n at time t and V_{n_min} and V_{n_max} represent respectively the minimum and maximum admissible voltage level for that particular node.

EQUATION 27

$$V_{n\_min} \leq V_{n,t} \leq V_{n\_max} \qquad \forall n, t$$

Similarly to **EQUATION 27** also the voltage angle must not be out a certain range,see Equation **28**, (T. Brown, J. Hörsch, and D. Schlachtberger, 2018).

Equation **28**

$$\delta_{n\_min} \leq \delta_{n,t} \leq \delta_{n\_max} \qquad \forall n, t$$

Finally, the power flow should be executed to compute the magnitude and angle of the voltage in each node. Given the complexity of the problem, a linearized power flow is adopted. It assumes that: *i)* reactive power flow decouples from active power flow; *ii)* there are no large voltage magnitude variations; *iii)* voltage angles differences across branches are small enough that $\sin\theta \cong \theta$ and *iv)* branch resistances are negligible when compared to branch reactances. Having defined these assumptions, the linear equation of the power flow can be written as in **EQUATION 29** (T. Brown, J. Hörsch, and D. Schlachtberger, 2018), which can be used to retrieve the values of the voltage angle in each node.

EQUATION 29

$$P_n = \sum_m (KBK^T)_{nm}\theta_m - \sum_l K_{nl} b_l \theta_l^{shift}$$

Within this study, a combination of Market and Network (Re-Dispatch) simulations is adopted for the benchmark of the different grid options. **FIGURE 59** shows the main categories and indicators used in the CBA to benchmark radial and hybrid grid layouts.

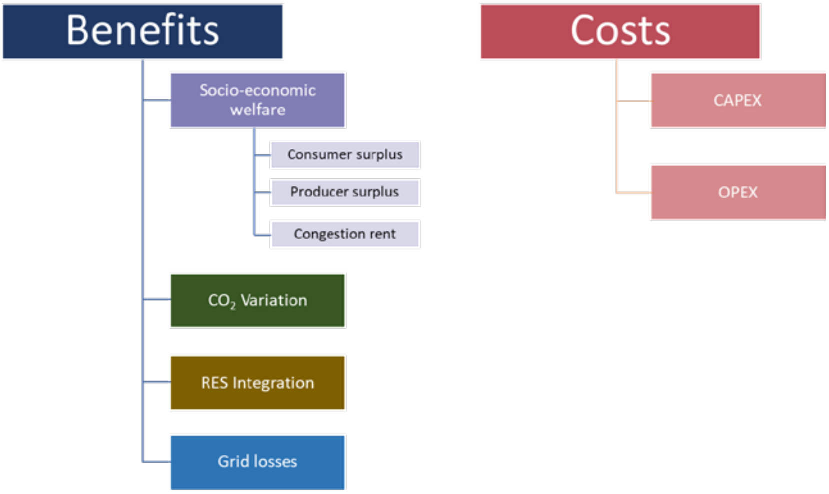

FIGURE 59: MAIN CATEGORIES OF THE CBA

While network studies can provide only information about RES integration and grid losses, changes in social economic welfare for the two options are computed both via Market and Re-dispatch simulations (see **FIGURE 60**). The radial case is considered as the reference network.

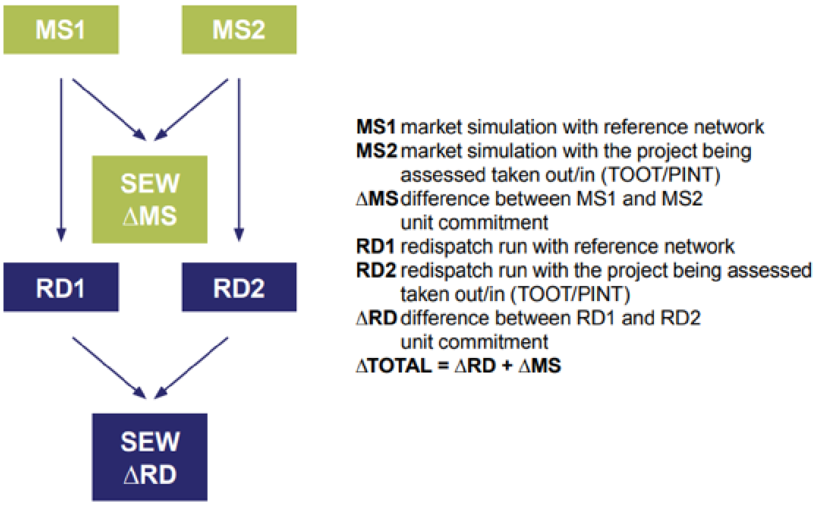

FIGURE 60: COMPUTATION OF SOCIO-ECONOMIC WELFARE VIA MARKET SIMULATIONS AND RE-DISPATCH SIMULATIONS.

3.3. Grid connection results

In this section, the grid configuration is described for each scenario. The two different grid layouts are designed considering the cost catalogue presented in the Appendix 5.

3.3.1. Radial connection - Counterfactual

The radial counterfactual connection for the four scenarios is illustrated in Figure 61 to Figure 64. Despite being illustrated as straight lines in the figures, deviations in the connections between ORE plants and substations around constrained areas and water depth are taken into account.

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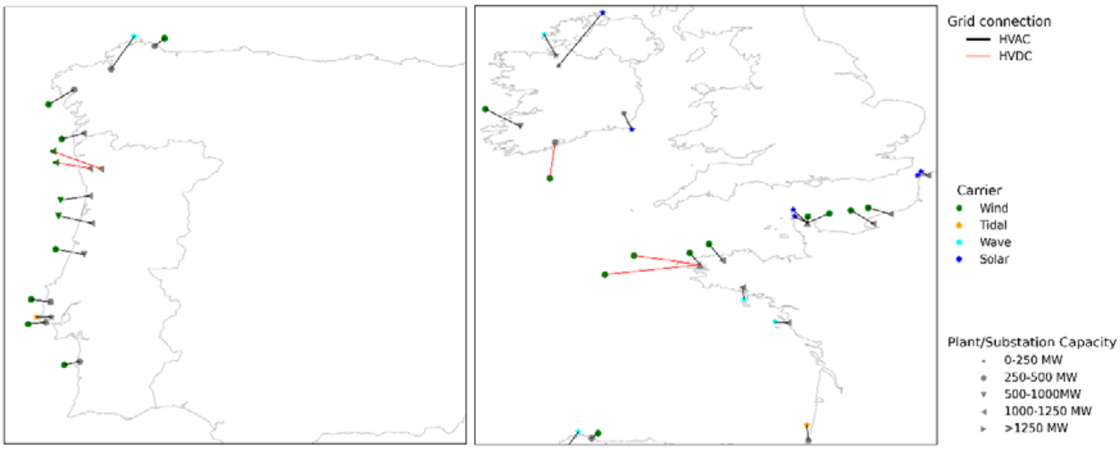

FIGURE 61: RADIAL COUNTERFACTUAL CONNECTION OF ORE PLANTS FOR THE CURRENT PATHWAY SCENARIO 2030

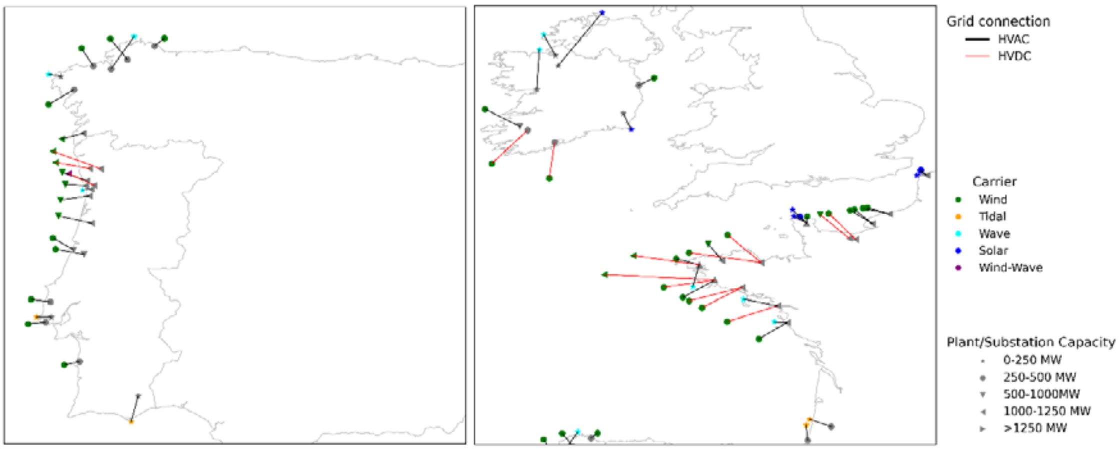

FIGURE 62: RADIAL COUNTERFACTUAL CONNECTION OF ORE PLANTS FOR THE AMBITIOUS SCENARIO 2030

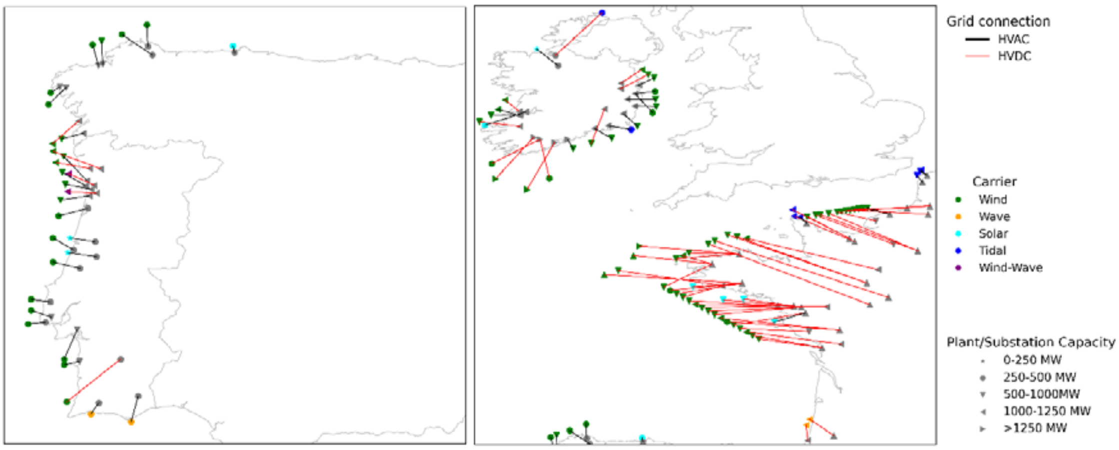

FIGURE 63: RADIAL COUNTERFACTUAL CONNECTION OF ORE PLANTS FOR THE CURRENT PATHWAY SCENARIO 2050

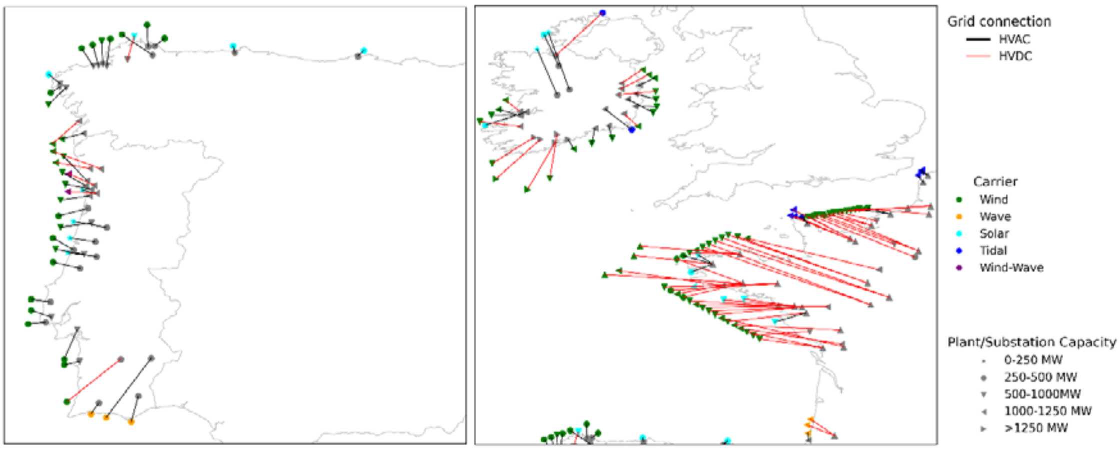

FIGURE 64: RADIAL COUNTERFACTUAL CONNECTION OF ORE PLANTS FOR THE AMBITIOUS SCENARIO 2050

3.3.2. Radial connection - Integrated

The radial integrated connection for the four scenarios is illustrated in Figure 65 to Figure 68, and it results from the counterfactual design as explained in Section 3.2.2.2.2. Despite being illustrated as straight lines in the figures, deviations in the connections between ORE plants and substations around constrained areas and water depth are taken into account.

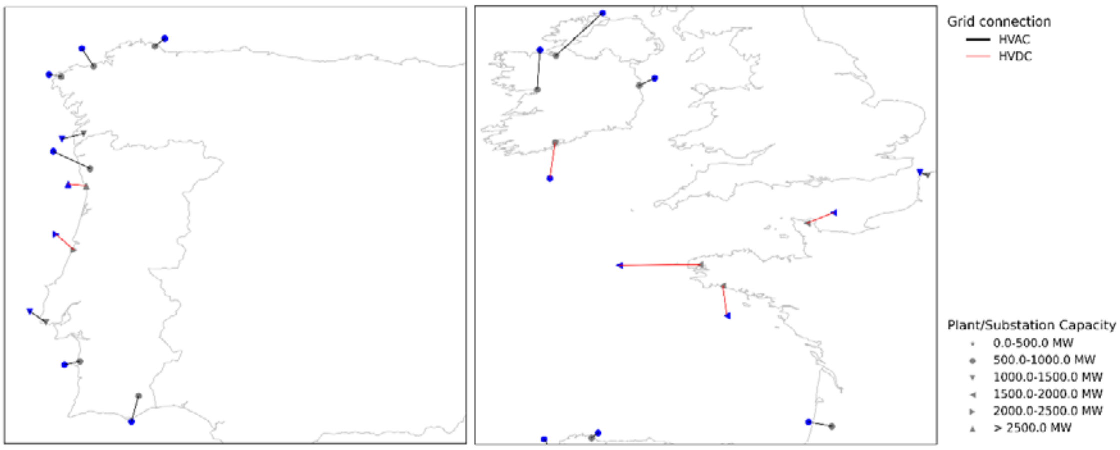

FIGURE 65: RADIAL INTEGRATED CONNECTION OF ORE PLANTS FOR THE CURRENT PATHWAY SCENARIO 2030

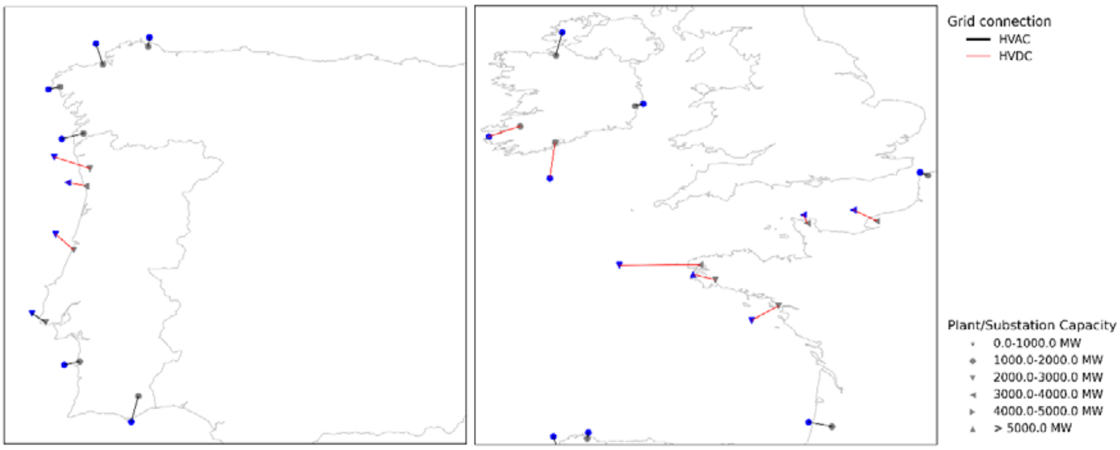

FIGURE 66: RADIAL INTEGRATED CONNECTION OF ORE PLANTS FOR THE AMBITIOUS SCENARIO 2030

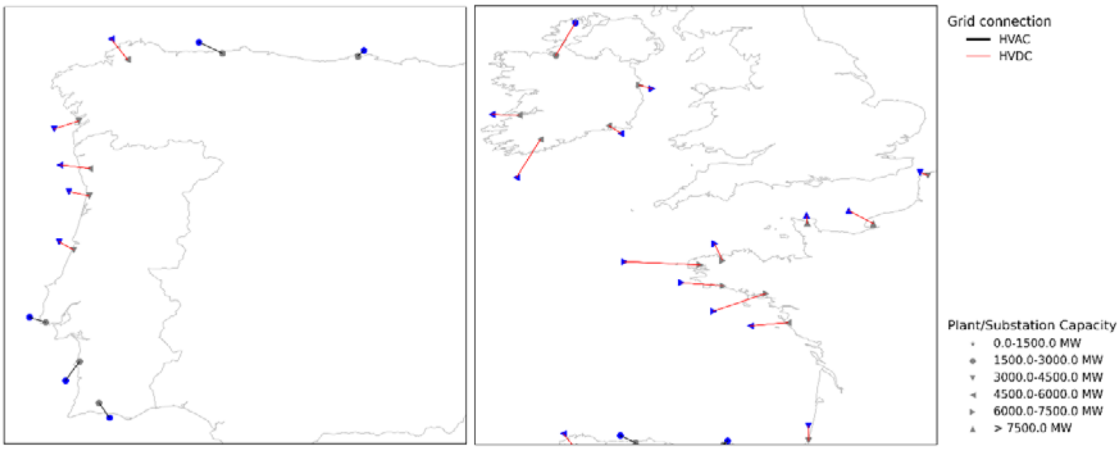

FIGURE 67: RADIAL INTEGRATED CONNECTION OF ORE PLANTS FOR THE CURRENT PATHWAY SCENARIO 2050

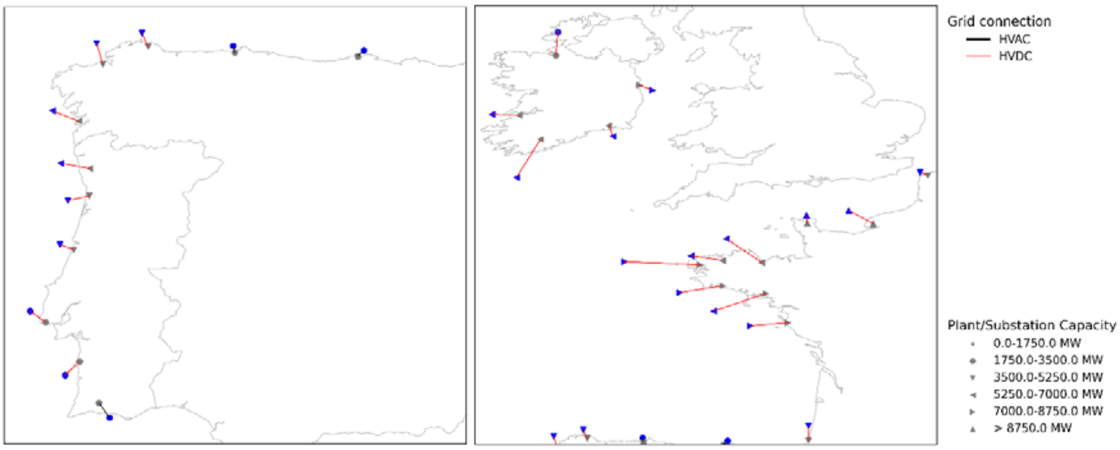

FIGURE 68: RADIAL INTEGRATED CONNECTION OF ORE PLANTS FOR THE AMBITIOUS SCENARIO 2050

3.3.3. Hybrid connection

The hybrid-case consists of a number of ORE farms radially connected to onshore substations, while others are connected to offshore hubs. These hubs are then connected via hub-to-hub interconnectors.

Possible interconnections have been identified between Ireland and France, in light with the ENTSO-E TYNDP that foresees an HVDC interconnection (TR 107 - Celtic Interconnector) linking North-West France and South-East Ireland. The status is permitting, and the commissioning date is currently set to 2027 (see Figure 69), with a capacity of 700 MW. It is possible to envisage technical solutions where the connection of the production blocks is realised in parallel with the HVDC link or where the two projects are integrated as a single multiple HVDC link. Within this study, the ENTSO-E interconnection project is considered as stand-alone HVDC link, while the identified interconnections work in parallel to it.

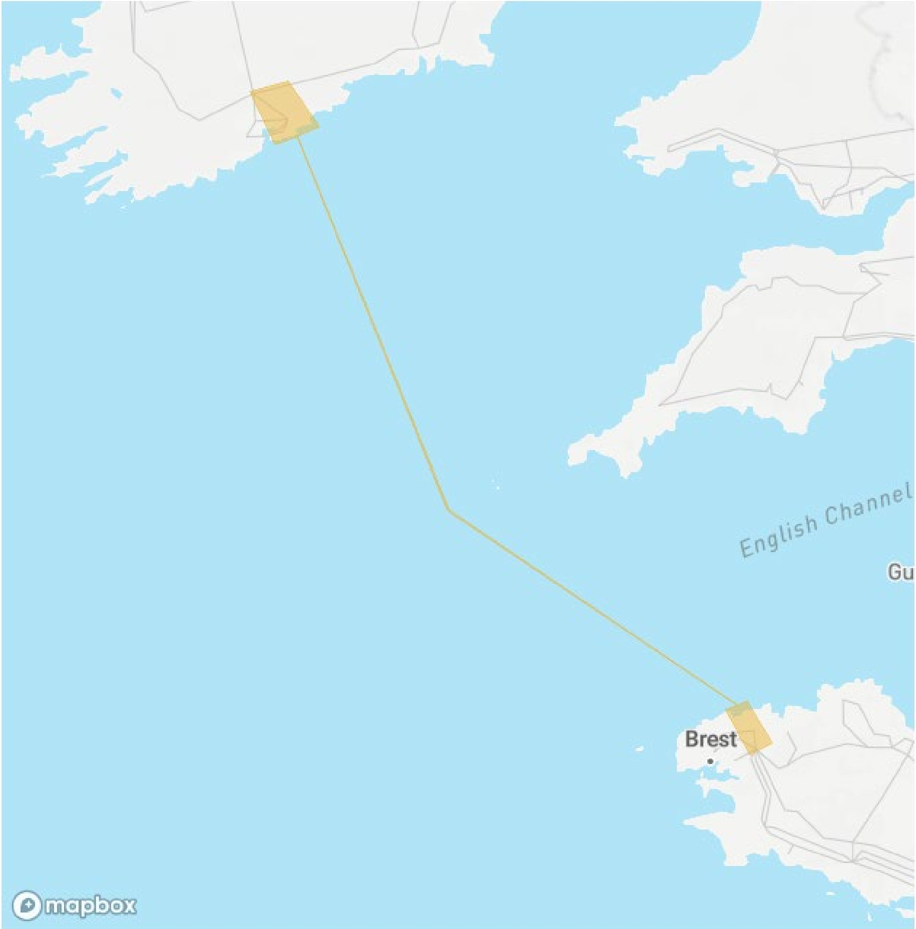

FIGURE 69: PLANNED INTERCONNECTION FRANCE-IRELAND[67]

In the identified scenarios, possible interconnections between Spain and Portugal are identified. Notably, there is one onshore project in the ENTSO-E TYNDP situated in the same region of the identified interconnection: TR 4 - Interconnection Portugal-Spain (see Figure 70), whose commissioned date is set to 2024. This project is envisioned to strengthen the Internal Energy Market and reach a completely operational Iberian Electricity Market. It is complemented by internal grid reinforcement in the north of Portugal and North-West of Spain. Neither of these projects have a direct impact on the layout of the optional grid connection, but if all of them are realised the respective transmission grids will be better equipped to accept injections of power from the production blocks. Within this study, the offshore interconnections between Spain and Portugal are considered as a supplement to the TYNDP project.

[67] From ENTSO-E TYNDP map : https://tyndp2022-project-platform.azurewebsites.net/projectsheets/transmission/107

FIGURE 70: PLANNED ONSHORE INTERCONNECTION PORTUGAL-SPAIN[68]

The hybrid configurations for the four scenarios, which include hybrid projects, are illustrated in Figure 71 to Figure 74. Despite being represented as straight lines in the figures, deviations in the connections between ORE plants and substations around constrained areas and water depth are included. Table 3-3 and Table 3-4 summarise the identified interconnections and their optimal capacity, for all the scenarios at issue.

TABLE 3-3: SUMMARY INTERCONNECTIONS 2030 SCENARIOS

	Current pathway 2030			Ambitious Scenario 2030		
	Capacity [MW]	Length [km]	Cost[M€]	Capacity [MW]	Length [km]	Cost[M€]
Interconnection PT-ES	500	25	21	1000	35	43
Interconnection IE-FR	800	270	270	1000	270	337

TABLE 3-4: SUMMARY INTERCONNECTION 2050 SCENARIOS

	Current pathway 2050			Ambitious Scenario 2050		
	Capacity [MW]	Length [km]	Cost[€]	Capacity [MW]	Length [km]	Cost[€]
Interconnection PT-ES	900	70	106	1500	105	197
Interconnection IE-FR	1500	260	488	1500	260	487

[68] From ENTSO-E TYNDP map : https://tyndp2022-project-platform.azurewebsites.net/projectsheets/transmission/4

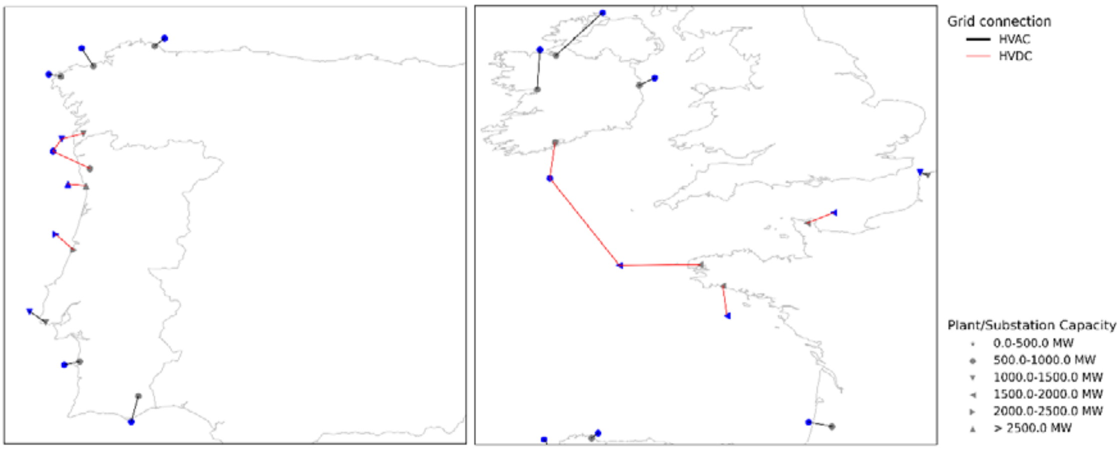

FIGURE 71: HYBRID CONFIGURATION FOR THE CURRENT PATHWAY SCENARIO 2030

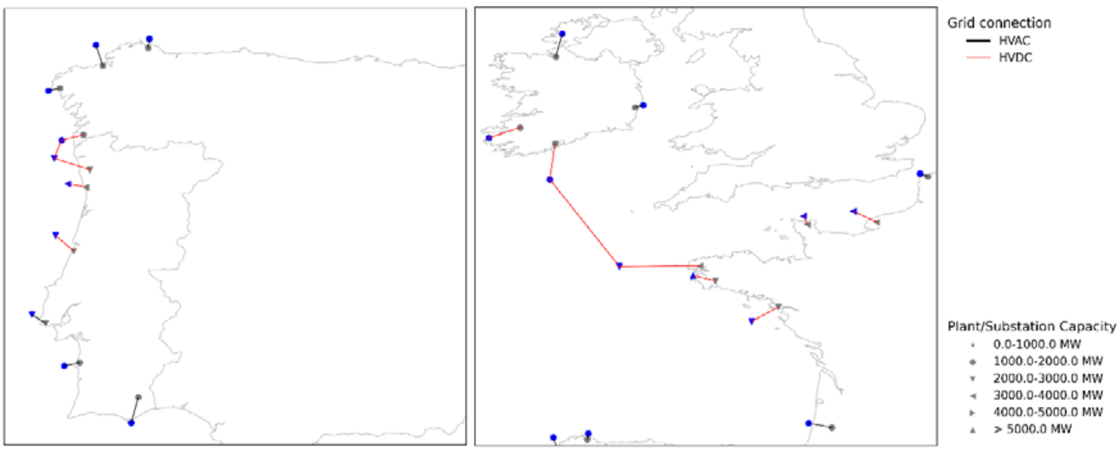

FIGURE 72: HYBRID CONFIGURATION FOR THE AMBITIOUS SCENARIO 2030

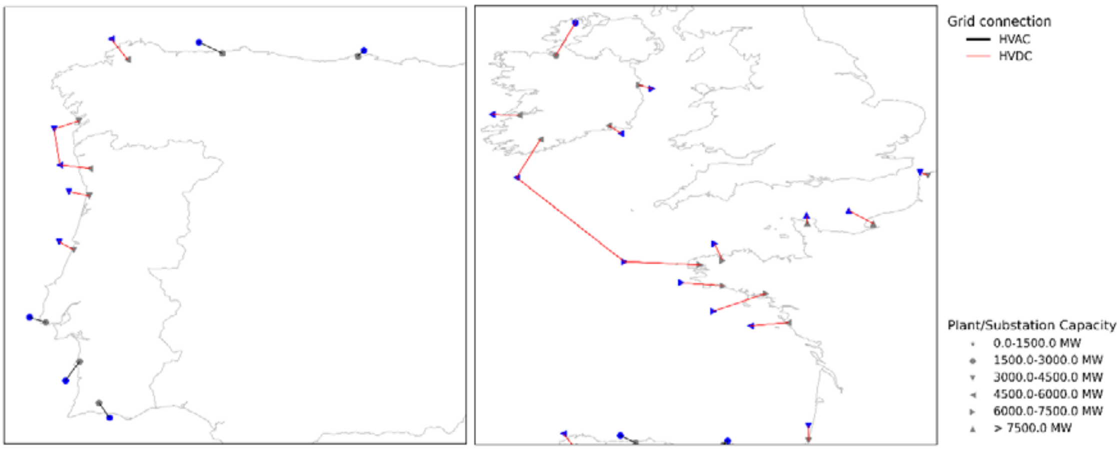

FIGURE 73: HYBRID CONFIGURATION FOR THE CURRENT PATHWAY SCENARIO 2050

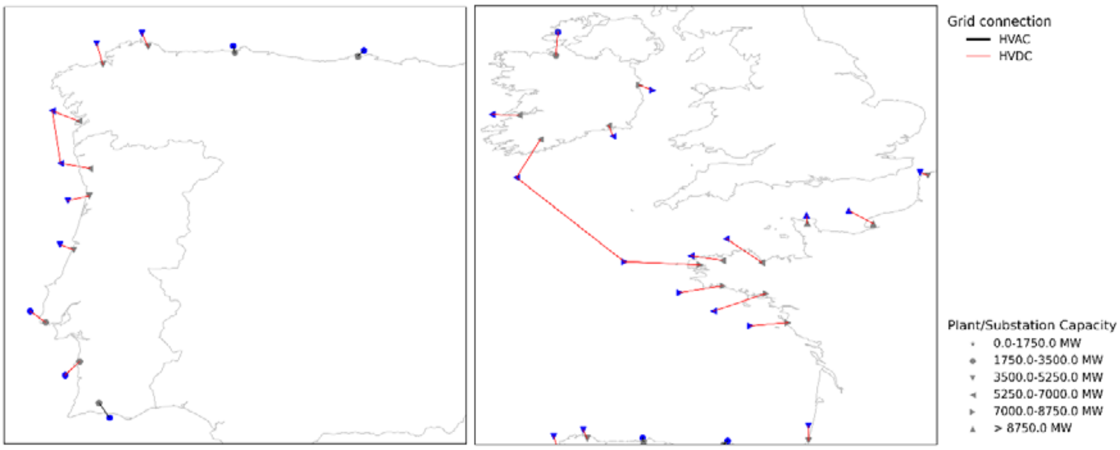

FIGURE 74 : HYBRID CONFIGURATION FOR THE AMBITIOUS SCENARIO 2050

3.4. Cost-benefit analysis for the production scenarios and grid options

A Cost-Benefit Analysis (CBA) of the different production scenarios and grid options highlights the main differences in term of:

- CAPEX and OPEX
  - CAPEX and OPEX for offshore generation
  - CAPEX and OPEX for different offshore grid configurations
- Socioeconomic parameters
  - Social welfare (producer surplus, consumer surplus and congestion rent)
  - Environmental impact (savings in CO_2 emissions)
- RES integration and curtailment

CAPEX and OPEX for the different grid options, as well as resistive losses and cost of offshore power generation are the results of the 2 previous chapters and their deployment in the production scenarios. Socioeconomic parameters (producer surplus, consumer surplus, congestion rent) are the result of extensive power market modelling of the different production scenarios and grid options.

Cost and benefits are summarised to show the effect on the Atlantic region as a whole, rather than for each Member State, since positive effects for one Member State could provoke negative impacts on another or more Member States.

3.4.1. CBA for 2030 scenarios

In this section the results of the CBA are illustrated for the following scenarios:

- Current pathway radial 2030, detailed in Section 2.2.1;
- Current pathway hybrid 2030, 2030 current pathway scenario with interconnections between Portugal and Spain and France and Ireland (see Section 2.2.1);
- Ambitious scenario radial 2030 – 2030 ambitious scenario with radial connection (see Section 2.2.2);
- Ambitious scenario radial 2030 - 2030 ambitious scenario with interconnections between Portugal and Spain and France and Ireland (see Section 2.2.2).

Socioeconomic effects and CO_2 emissions are simulated with EDP's power market/energy dispatch model, described in Section 3.2.2. All analyses are based on a single model year, either 2030 or 2050, while offshore energy production is based on a single weather year averaged over a 20-years database. The same transmission capacity was assumed for both model years, and the transmission system was modelled considering its current status and including ENTSO-E TYNDP projects. For the evaluation of the interconnection options (mesh configuration), this study only compares the respective scenario without the interconnection to the same scenario with interconnectors.

3.4.1.1 CAPEX, OPEX and RES integration

Figure 75 shows a comparison between the different 2030 production scenarios and grid options, in terms of RES integration and the CAPEX levels required for these investments. The CAPEX levels are the total levels expressed in 2022 real terms; thus, they should be interpreted as the investments necessary to deploy offshore power generation and grid connection up to 2030 to reach a total offshore capacity of 14.5 GW in the current pathway scenario (see Section 2.2.1) and 27.8 GW in the ambitious scenario (see Section 2.2.2).

The total CAPEX of integrating about 14.5 GW in the current pathway scenario, including grid connection, is around 40.3-40.6 billion € and around 68.3-68.8 billion € to integrate 27.8 GW in the ambitious scenario, depending on whether interconnectors are integrated or not (see Figure 75).

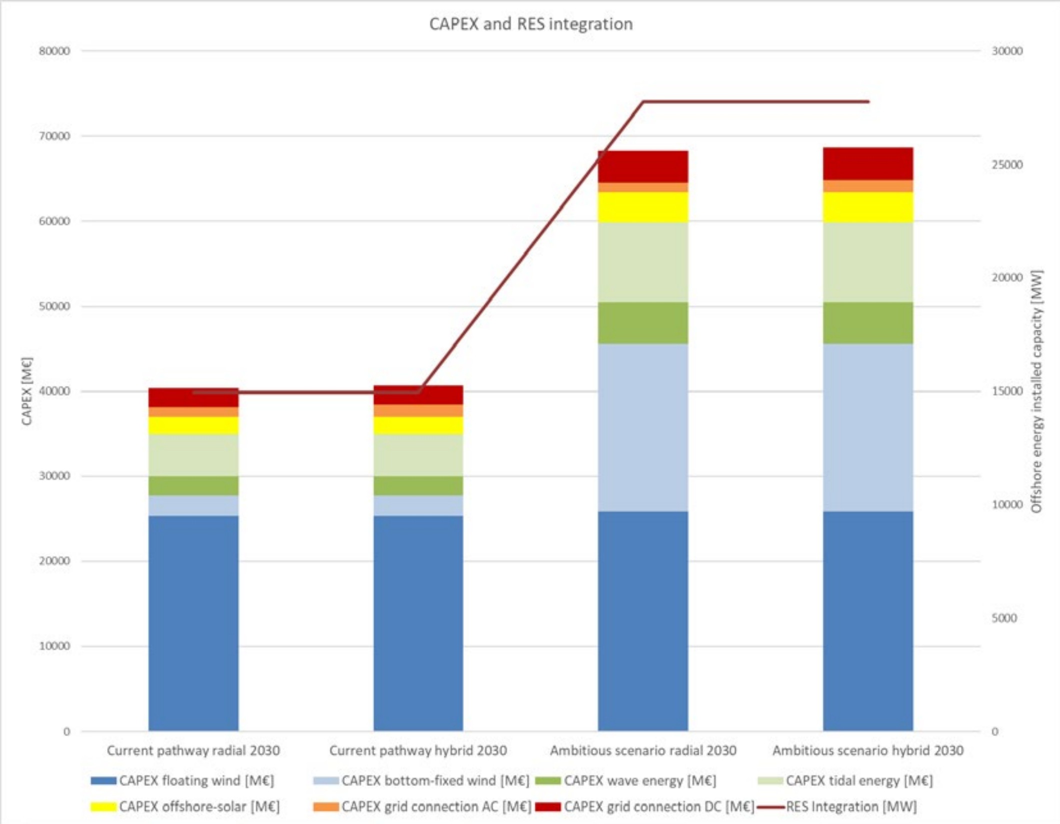

FIGURE 75: CAPEX AND RES INTEGRATION FOR THE VARIOUS 2030 PRODUCTION SCENARIOS AND GRID OPTIONS

Table 3-5 shows a comparison between the different 2030 grid options in terms of CAPEX, OPEX and losses for all the identified production scenarios. The analysis accounts only for resistive losses in the offshore grid.

The hybrid configuration, in the case of the current pathway, would require extra 291 M€ of investment in CAPEX, and 6 M€/year more in OPEX. This configuration leads to higher losses, as it offers different paths for energy exchange between countries. In the current pathway these losses increase stands at 9 GWh/year.

The hybrid configuration in the ambitious scenarios leads to a CAPEX increase of 380 M€, while the OPEX increases by 3 M€/year. Resistive losses are estimated to increase by 24 GWh/year.

TABLE 3-5 : COSTS AND LOSSES FOR THE 2030 PRODUCTION SCENARIOS

Country	CAPEX (M€)				OPEX (M€/year)				Losses (GWh/year)			
	Current pathway radial 2030	Current pathway hybrid 2030	Ambitious scenario radial 2030	Ambitious scenario hybrid 2030	Current pathway radial 2030	Current pathway hybrid 2030	Ambitious scenario radial 2030	Ambitious scenario hybrid 2030	Current pathway radial 2030	Current pathway hybrid 2030	Ambitious scenario radial 2030	Ambitious scenario hybrid 2030
ES	5 302	5 313	8 220	8 241	3,2	5,1	4,3	6,7	18	17	26	27
PT	15 512	15 522	19 890	19 912	9,4	10,3	10,2	10,4	25	23	30	31
FR	15 388	15 523	33 629	33 798	9,4	10,9	14,1	14,3	69	50	64	75
IE	4 153	4 288	6 569	6 738	4,1	6,3	6,0	6,2	25	56	32	43
Atlantic region	40 355	40 646	68 308	68 688	26,0	32,6	34,5	37,5	137	146	153	177

3.4.1.2 Social welfare results

Based on the energy dispatch modelling results, the Ambitious Scenario shows a significant increase in the consumer surplus, due to generally lower prices (see Figure 76): this situation occurs due to the high volume of RES generation, with low and close-to zero marginal price, brought into the market. Similarly, producer surplus increase mainly due to the multi-market participation: renewable assets can sell energy into market where the energy price is tendentially higher so to increase their revenues and they can see their curtailment being reduced.

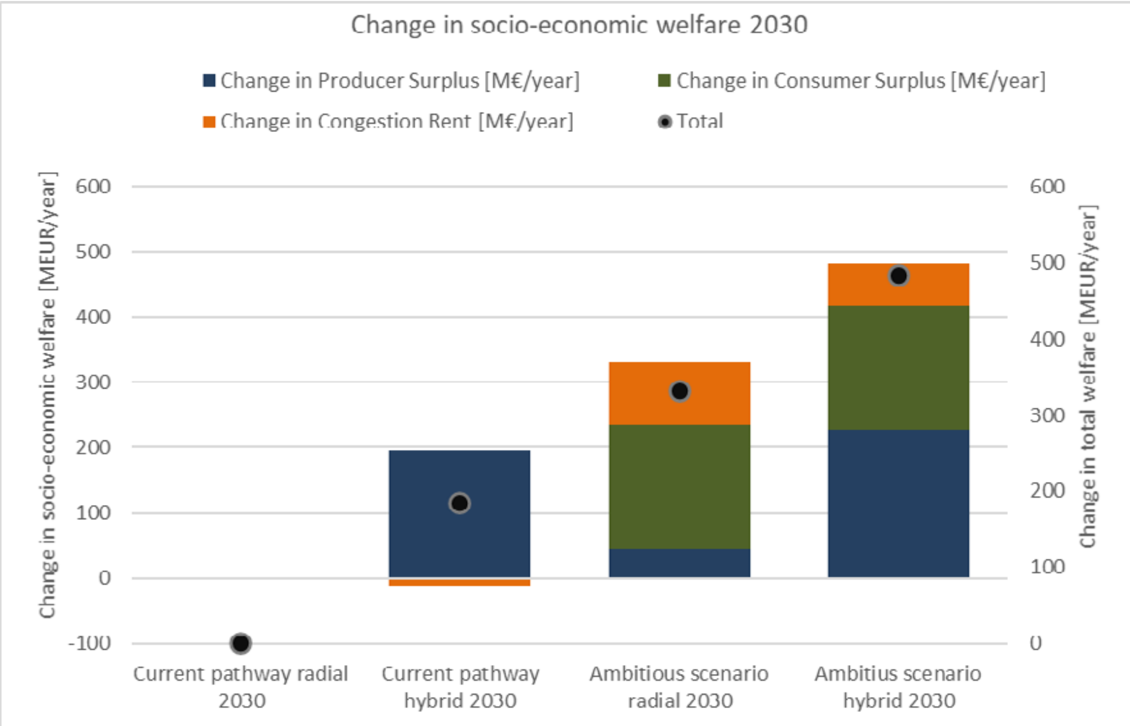

FIGURE 76 : CHANGE IN SOCIOECONOMIC WELFARE FOR 2030 PRODUCTION SCENARIOS AND GRID OPTIONS, COMPARED TO THE CURRENT PATHWAY SCENARIO WITH RADIAL CONNECTION

The hybrid configuration in the current pathway increased the total social welfare by 183 M€/year, as a result of a combined increase of producer surplus by 195 M€/year and a reduction of congestion rent by 12 M€/year.

The Ambitious Scenario brings an increase of social welfare around 331- 482 M€/year: the hybrid configuration is the one with the highest increase.

3.4.1.3 Savings in CO_2 emissions

Figure 58 shows the CO_2 emission savings of the different production scenarios and grid options compared with the current pathway with radial connection. The hybrid layout produced savings of around 2700 Kton of CO_2 annually in the current pathway by replacing fossil-fuelled generation.
CO_2 savings increased up to 5000 Kton in the ambitious scenario, given the higher penetration of offshore energy. Interconnections in the ambitious scenario would contribute to annual CO_2 emissions savings of about 1900 kTon more annually.

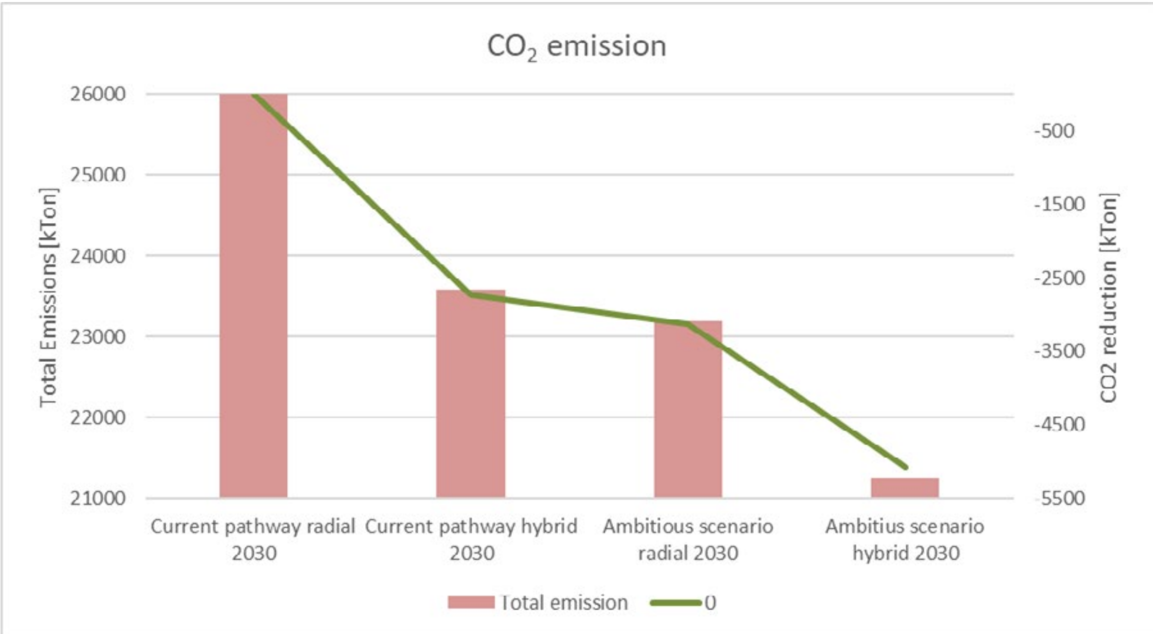

FIGURE 77: CO_2 EMISSIONS SAVINGS OF THE PRODUCTION SCENARIOS AND THEIR GRID OPTIONS COMPARED WITH THE CURRENT PATHWAY 2030 SCENARIO WITH A RADIAL CONNECTION

3.4.1.4 Energy mix and ORE curtailment

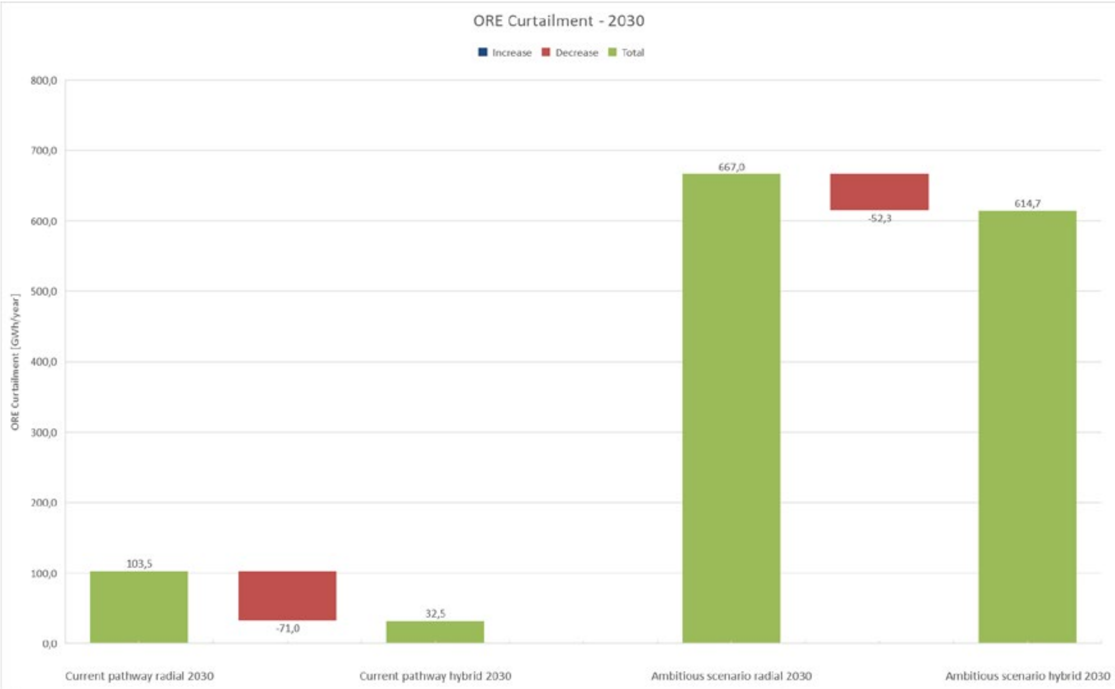

FIGURE 78 : ORE CURTAILMENT IN THE DIFFERENT PRODUCTION SCENARIOS 2030

Figure 78 shows the ORE curtailment in the 2030 production scenarios for the different grid options. Either case, hybrid grid would allow to reduce the overall curtailment thanks to the coordinated approach. In absolute terms, hybrid grid would allow to reduce ORE curtailment in the current pathway scenario by 71 GWh/year and by 52 GWh/year in the ambitious scenario.

Figure 79 shows how the electricity demand in the Atlantic region would be supplied by the different energy sources in 2030, for the different production scenarios and grid options.

With the current pathway, offshore renewable energy would cover up to 8-9% of the whole electricity demand, of which 87% is supplied by offshore-wind. The situation does not change much with the introduction of the hybrid option, as it increases by 1%.

With the ambitious scenario, the penetration of offshore renewables increases up to 17%, with wind covering 14-16%.

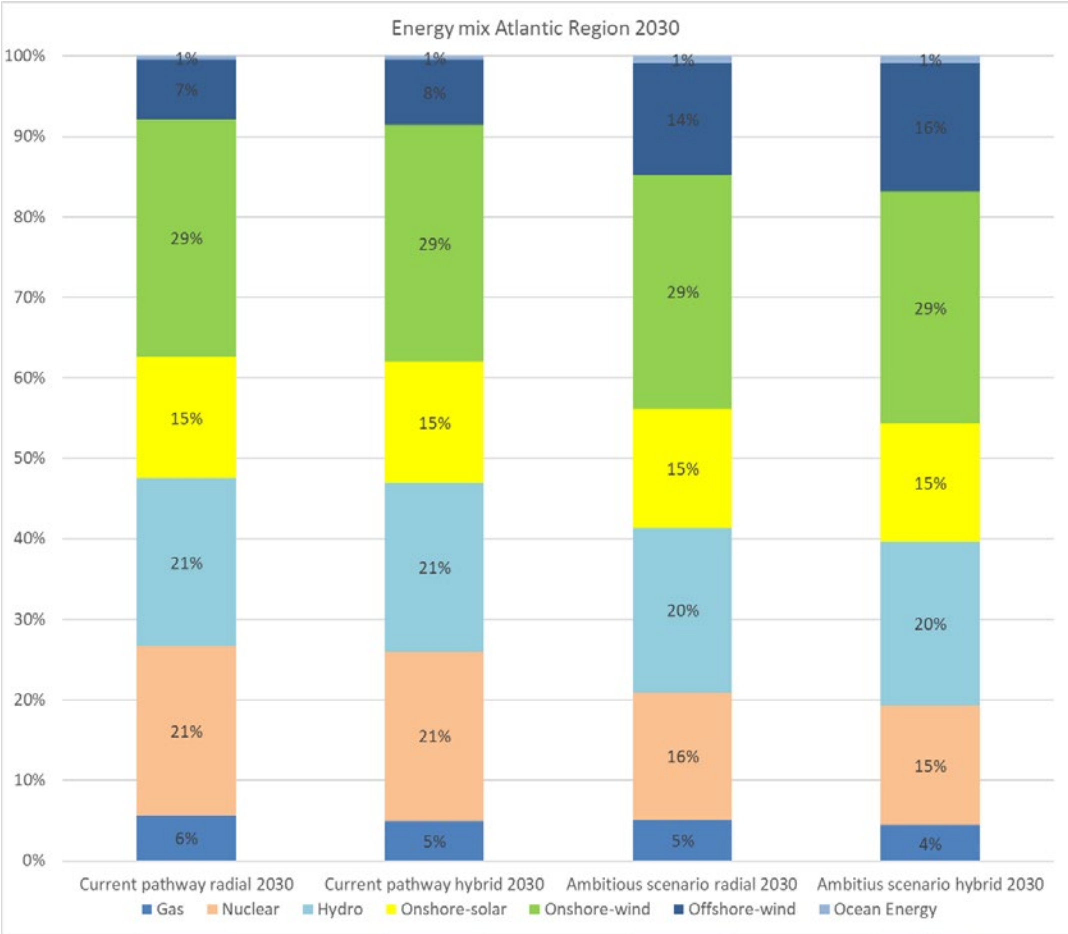

FIGURE 79: ENERGY MIX ATLANTIC REGION 2030

3.4.2. CBA for 2050 scenarios

In this section the results of the CBA are presented for the following scenarios:

- Current pathway radial 2050, illustrated in Section 2.2.1;
- Current pathway hybrid 2050, with interconnections between Portugal and Spain and France and Ireland;
- Ambitious scenario radial 2050 with radial connection;
- Ambitious scenario hybrid 2050 with interconnections between Portugal and Spain and France and Ireland (see Section 2.2.2).

3.4.2.1 CAPEX, OPEX and RES integration

Figure 80 shows a comparison between the different 2050 production scenarios and grid options, in terms of RES integration and CAPEX levels required for these investments. The CAPEX levels are total levels expressed in 2022 real terms; thus, they should be interpreted as the investments necessary to deploy offshore power generation and grid connection up to 2050 to reach a total offshore capacity of 76 GW in the current pathway scenario (see Section Section 2.2.1) and 96.5 GW in the ambitious scenario (see Section 2.2.2).

The total CAPEX of integrating about 76 GW in the current pathway scenario, including grid connection, is around 144-144.6 billion € and around 180.8-181.5 billion € to integrate

96.5 GW in the Ambitious Scenario depending on whether interconnectors are integrated or not.

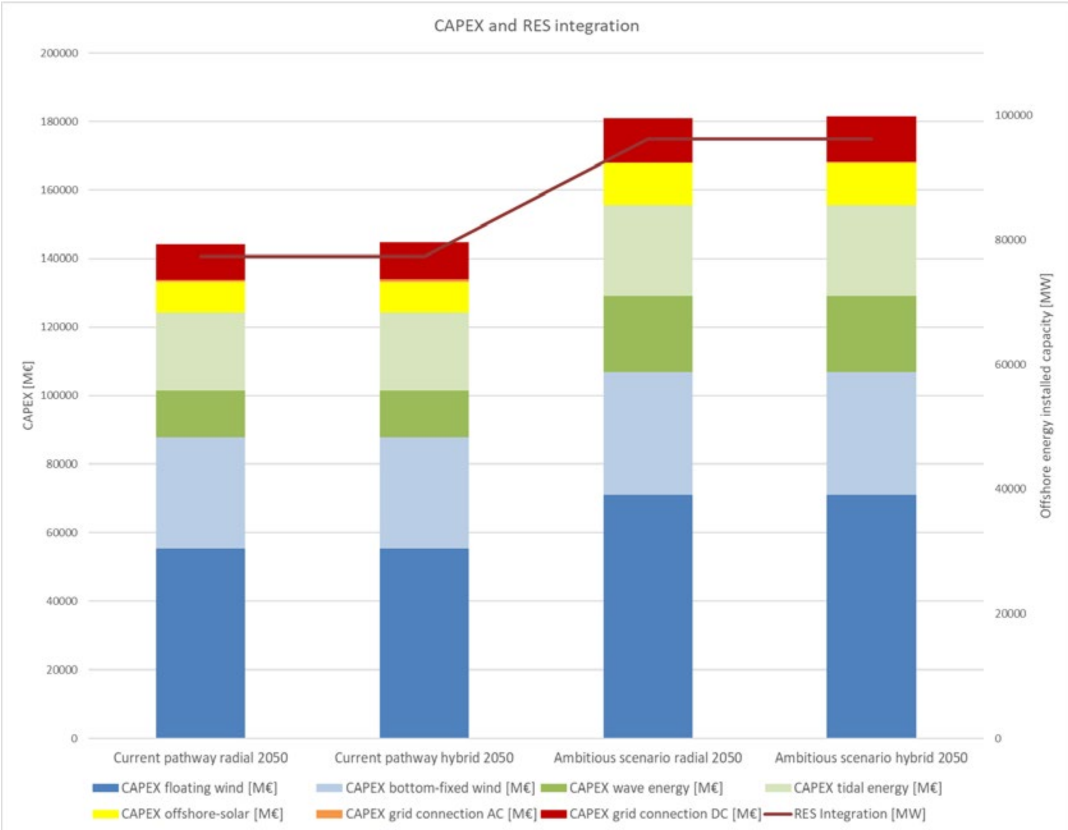

FIGURE 80: CAPEX AND RES INTEGRATION FOR THE VARIOUS 2050 PRODUCTION SCENARIOS AND GRID OPTIONS

Table 3-6 shows a comparison between the different 2050 grid options in terms of CAPEX, OPEX and losses for all the identified production scenarios. The analysis accounts only for resistive losses in the offshore grid.

The mesh configuration, in the case of the current pathway, would require extra 600 M€ of investment in CAPEX, and 2 M€/year more in OPEX. This configuration leads to higher losses, as it offers different paths for energy exchange between countries.

In the current pathway, losses increase settled at 16 GWh/year. The hybrid configuration in the ambitious scenarios led to a CAPEX increase of 600 M€, while the OPEX increased by 3 M€/year. Resistive losses are estimated to increase by 11 GWh/year.

TABLE 3-6 : COSTS AND LOSSES FOR THE 2050 PRODUCTION SCENARIOS

Country	CAPEX (M€)				OPEX (M€/year)				Losses (GWh/year)			
	Current pathway radial 2050	Current pathway hybrid 2050	Ambitious scenario radial 2050	Ambitious scenario hybrid 2050	Current pathway radial 2050	Current pathway hybrid 2050	Ambitious scenario radial 2050	Ambitious scenario hybrid 2050	Current pathway radial 2050	Current pathway hybrid 2050	Ambitious scenario radial 2050	Ambitious scenario hybrid 2050
ES	12 040	12 093	16 621	16 719	300,1	300,8	382,0	382,6	31	32	47	50
PT	17 705	17 758	23 335	23 433	449,0	449,2	599,8	601,2	35	36	53	56
FR	86 430	86 674	108 194	108 438	1 897,3	1 897,7	2 354,4	2 354,9	534	541	800	803
IE	27 908	28 152	32 741	32 985	723,1	723,6	832,5	832,9	127	134	190	192
Atlantic region	144 083	144 677	180 891	181 575	3 369,5	3 371,4	4 168,7	4 171,6	727	743	1 090	1 101

3.4.2.2 Social welfare results

The Ambitious Scenario shows an increase in the consumer surplus and a reduction of the producer surplus due to generally lower prices (see Figure 81). This situation occurs due to the high volume of RES generation, with low and close-to zero marginal price, brought into the market.

The hybrid configuration in the current pathway reduced the total social welfare by 5 M€/year, as it leads to a high reduction of producer surplus (of around 524 M€/year) that it is not compensated by a sufficient increase of consumer surplus (392 M€/year) and congestion rent (126 M€/year).

The Ambitious scenario radial case introduced an increase of the social welfare of 86 M€/year, while the hybrid case contributed to an increase of the social welfare by roughly 176 M€/year.

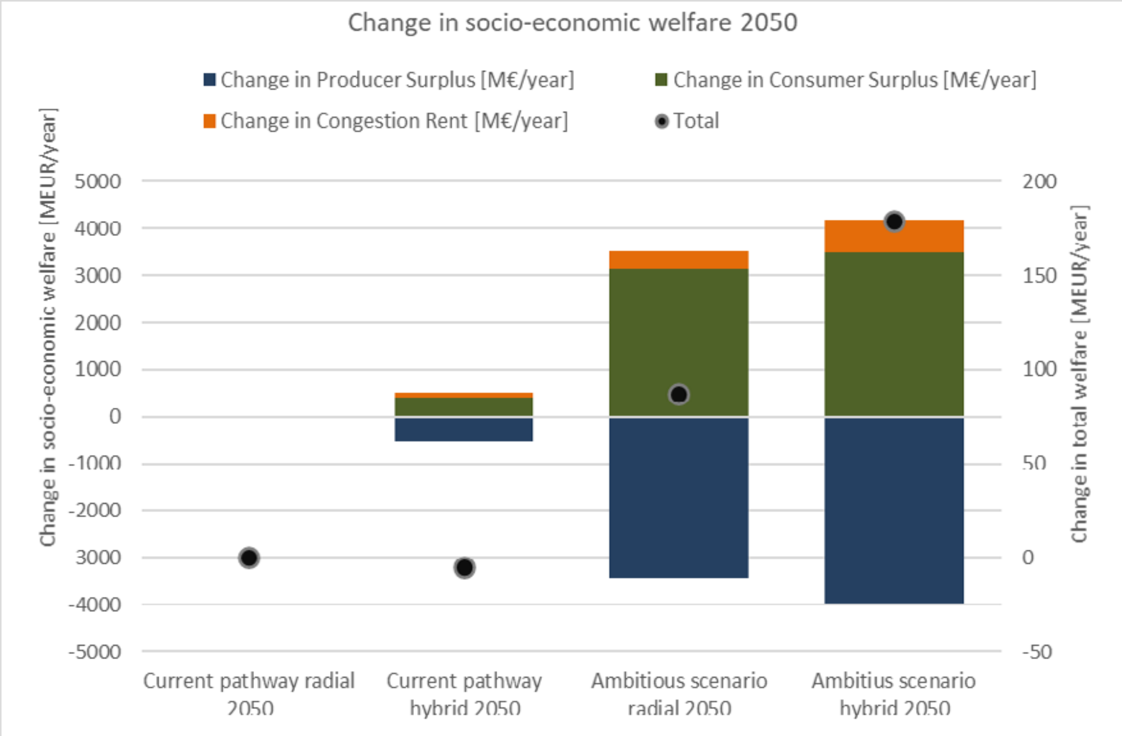

FIGURE 81 : CHANGE IN SOCIOECONOMIC WELFARE FOR 2050 PRODUCTION SCENARIOS AND GRID OPTIONS, COMPARED TO THE CURRENT PATHWAY SCENARIO WITH RADIAL CONNECTION

3.4.2.3 Savings in CO_2 emissions

Figure 82 shows the CO_2 emission savings of the different production scenarios and grid options compared with the current pathway with radial connection. The hybrid layout registered savings of around 5 kTon of CO_2 annually in the current pathway by replacing fossil-fuelled generation. CO_2 savings increased up to 40-45 kTon in the ambitious scenario.

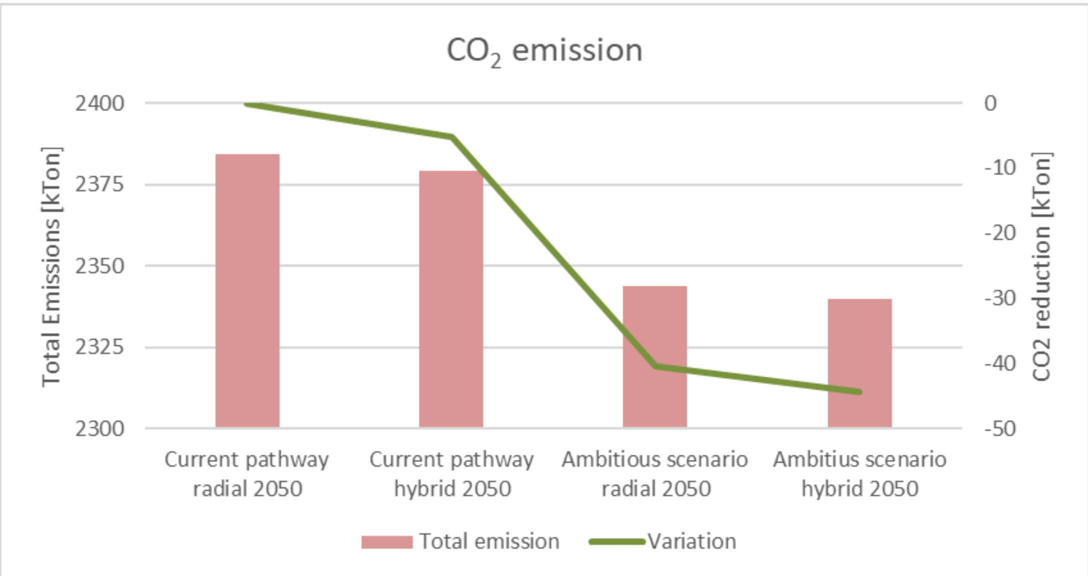

FIGURE 82: CO_2 EMISSIONS SAVINGS OF THE PRODUCTION SCENARIOS AND THEIR GRID OPTIONS COMPARED WITH THE CURRENT PATHWAY 2050 SCENARIO WITH A RADIAL CONNECTION

3.4.2.4 Energy mix and ORE curtailment

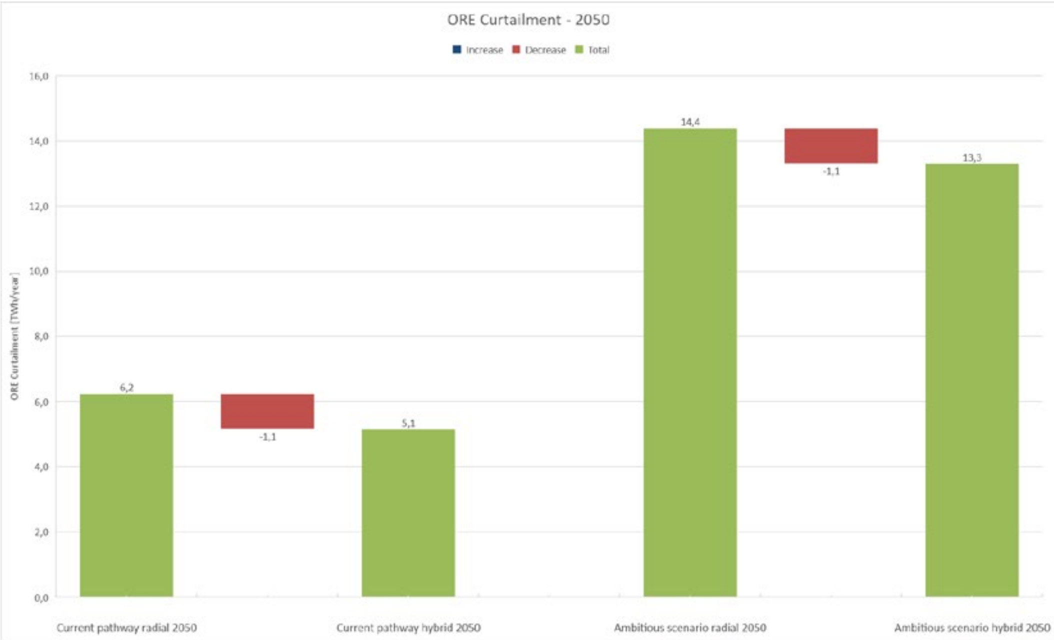

FIGURE 83: ORE CURTAILMENT IN THE DIFFERENT PRODUCTION SCENARIOS 2050

Figure 83 shows the ORE curtailment in the 2050 production scenarios for the different grid options. Either case, hybrid grid would allow to reduce the overall curtailment thanks to the coordinated approach. In absolute terms, hybrid grid would allow to reduce ORE curtailment in the current pathway and ambitious scenario by 1 TWh/year.

Figure 84 shows how the electricity demand in the Atlantic region would be supplied by the different energy sources in 2050, for the different production scenarios and grid options.

With the current pathway, offshore renewable energy would cover up to 29% of the whole electricity demand, of which 90% is supplied by offshore-wind. Introducing the hybrid configuration this share increased by 1%.

With the ambitious scenario, the penetration of offshore renewables increased up to 32-35%.

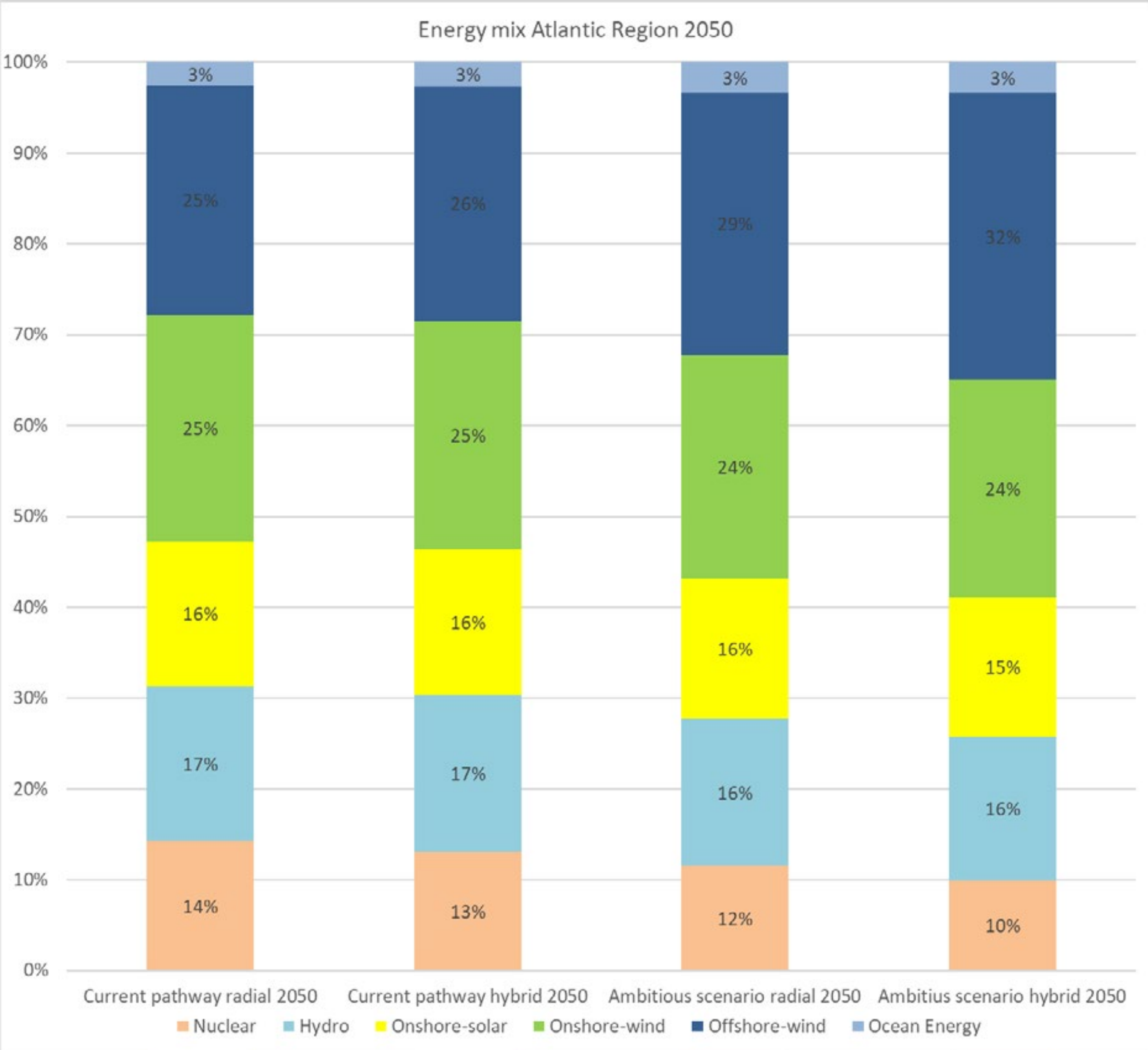

FIGURE 84: ENERGY MIX ATLANTIC REGION 2050

3.5. Conclusion Costs and estimated costs for grid reinforcement

All scenarios require considerable investments in offshore power generation and connection to the onshore grid. The total CAPEX of integrating 14.5 GW by 2030 in the current pathway scenario is around 40.3-40.6 billion €, whereas to integrate 27.8 GW by 2030 in the ambitious scenario is around 68-69 billion € depending on the grid option. This study shows how floating offshore wind would stand for 40-70% of the investments in offshore power generation, depending on the scenario, by 2030.

To achieve the RES integration of 76 GW in the current pathway scenario 2050 an investment of 144-145 billion € is required, that increases up to 180-182 billion € in the ambitious scenario, depending on the grid option, to integrate 96.5 GW.

For all production scenarios, the radial connection requires lower CAPEX and OPEX than the hybrid alternatives. The reason is that the hybrid alternatives require further cables to interconnect different production blocks. Nevertheless, CAPEX increase in this case is quite limited and sometimes compensated by socioeconomic improvements. On the downside, the radial alternatives provoke a decrease in security of supply, as the outage of a cable would mean the loss of its production block. However, the hybrid approach would require a bigger commitment in terms of policies as the whole group of production blocks should be realised as a common project.

For what concerns the hybrid alternatives, this study concludes that possible benefits exist in terms of increase of social welfare and CO_2 emission savings. In particular, for the 2030 production scenarios, the hybrid approach would bring increase of the social welfare by roughly 183 M€/year in the case of the current pathway scenario and around 330-480 M€/year in the case of the ambitious scenario. The situation slightly changes for the ambitious scenario, where the hybrid approach is not beneficial for the current pathway scenario, as it leads to socioeconomic decrease estimated at around 5 M€/year, whereas in the case of the ambitious scenario, the hybrid approach results in an increase of the social welfare of 176 M€/year.

Finally, in all the production scenarios, the hybrid approach leads to higher CO_2 savings and lower ORE curtailments.

Even though onshore grid reinforcments were not part of this study, a preliminary assessment was made, to estimate what is the needed upgrade that onshore transmission systems need to undergo in order to accommodate such high offshore energy capacity.

Table 3-7 summarises the estimated grid reinforcement for all the scenarios at stake in terms of new capacity and possible cost.

TABLE 3-7: ESTIMATED GRID REINFORCMENTS

	Current pathway 2030		Ambitious scenario 2030		Current pathway 2050		Ambitious scenario 2050	
	Power [GW]	Cost [M€]	Power [GW]	Cost [M€]	Power [GW]	Cost [M€]	Power [GW]	Cost [M€]
Atlantic region	2	25	3	42	49	988	59	1386

FIGURE 85: SUMMARY OF THE CBA FOR THE DIFFERENT PRODUCTION SCENARIOS AND GRID OPTIONS

4. IMPLEMENTATION CHALLENGES AND BARRIERS

In the study of ORE potential in the Atlantic Arc, section 4 identifies the key implementation challenges of non-technical nature, and provides an up-to-date analysis of these challenges, whether they concern nascent technologies (tidal, wave) or the expansion of more mature technologies (offshore wind).
Five main categories of non-technical implementation challenges are addressed: **Regulatory and administrative, Social-ecological, Economic and financial, MSP and Multi-use, Supply Chain**.

4.1.1. Methodology

To identify the most relevant and up-to-date non-technical implementation challenges to ORE technologies in the Atlantic region, we conducted an in-depth review of the scientific literature. This literature review is based on scientific papers published between January 2021 and December 2022, as these were assessed to be best suited to capture the most relevant challenges in a rapidly-evolving sector.)
The information was gathered from two main repository platforms for scientific publications (science Direct, Elsevier using two combinations of keywords: "**Marine renewable energy + Barriers"** and "**Offshore wind + Barriers"**. The raw results were filtered to exclude non-EU case studies and studies on technical challenges (blades, foundations, meteorological and physical marine conditions, etc.). The results were then further filtered to keep only peer reviewed publications.
In total, a database of 101 publications (Table 4-1) was built and a script allowed to automatically extract information according to the range of non-technical issues addressed. The full database is in Appendix.

TABLE 4-1 : NUMBER OF SCIENTIFIC PAPERS INCLUDED IN THE LITERATURE REVIEW ON ORE NON-TECHNICAL CHALLENGES.

Publication year / Keywords combination	2022	2021
MRE + Barriers	43	37
OW + Barriers	9	12
Total	52	49
	101	

The analysis of non-technical implementation barriers is complemented by considering the press releases from sectoral associations (e.g. WindEurope Press[69]). This complementary material provides an up-to-date information on economic and market challenges in connection to recent events, for instance implications related to the Covid pandemic and Russia's warwar of aggression against Ukraine.

[69] https://windeurope.org/newsroom/press-releases/

The European Commission assessment of the National Energy and Climate Plans (NECPs) for France, Ireland, Spain, and Portugal, includes an analysis of remaining gaps or challenges and recommendations[70]. These assessments reports were also considered for the analysis.

4.1.2. Results of the literature review – List of region-specific non-technical challenges

Table 4-2 below draws up a comprehensive list of the non-technical implementation challenges drawn up on the basis of the methodology described.

[70] EC, 2020, Assessment of the final national energy and climate plan of Ireland, SWD(2020) 906 final of 14.10.2020, Brussels, 32p.
EC, 2020, Assessment of the final national energy and climate plan of Spain, SWD(2020) 908 final of 14.10.2020, Brussels, 25p.
EC, 2020, Assessment of the final national energy and climate plan of France, SWD(2020) 909 final of 14.10.2020, Brussels, 27p.
EC, 2020, Assessment of the final national energy and climate plan of Portugal, SWD(2020) 921 final of 14.10.2020, Brussels, 25p.

TABLE 4-2 : LIST OF NON-TECHNICAL IMPLEMENTATION CHALLENGES TO THE DEVELOPMENT OF ORE IN THE EUROPEAN ATLANTIC ARC

Main category of non-technical implementation challenge	Specific non-technical challenge
Regulatory and administrative	• Timing of project approval and permitting, uncertainuncertain timeframe of administrative processes and legal actions • which are under development to address the specificities of OREthe nature and aspects of this activity Stakeholder engagement: uncertainties on processes and the consideration of competing positions and interests
Social-ecological	• Differences in the Environmental Impact Assessment (EIA) methodologies, as there is no widely accepted scientific methodology to support the comparability of EIA results • Organizational barriers to data access and sharing, stressing the need of an international standardized methods in data collection that would facilitate data transferability and new projects permitting efforts • Social perception of ecological impacts varies depending on the national versus local scale
Economic and financial	• The evolving national funding and market schemes addresses the challenges of: o enhancing private investments; o and reinforcing the attractiveness of national funding schemes by building new connections between stakeholders • Challenge of a geographic diversification of the value chain due to the increase in price of components. • Challenge of reducing the LCOE for future offshore projects by supporting investment costs.
MSP/Multi-use	• Lack of experiences on multi-uses: More examples of long-lasting coexistence could inspire new practices of multi-uses and improve the gain of Social Licence to Operate (SLO)

	• The necessity to address technical and non-technical issues simultaneously in the ORE planning, in line with the social sustainability approach expectations • Operational challenges linked to the technical compatibility of multiple activities in the same maritime area (colocation) • Anticipating possible additional costs and direct financial gain for the developers in relation with the multi-use
Supply Chain	• The need of increasing the visibility of the value chain as disrupted international supply chains may increase time for construction and costs of ORE projects • Strengthening infrastructure support, notably port facilities for components assembly and maintenance • Improve risks and safety management

4.1.3. Analysis of national strategies to mitigate non-technical implementation challenges in the Atlantic Region

Effective instruments, tools and strategies to address key implementation barriers already exist at the EU-level. For instance, important provisions on accelerating and streamlining permitting procedures are included in the EU Regulation on trans-European energy infrastructures (TEN-E Regulation).[71] Also, the 2020 EU Offshore Renewable Energy Strategy[72] is being successfully implemented. The Strategy proposed concrete actions to address non-technical barriers to the development of offshore renewable energy.

This section will not examine EU initiatives but will instead focus on national measures. Member States in the Atlantic region have undertaken many strategies to mitigate or overcome ORE non-technical implementation challenges identified in table 21. The following tables present a country-specific analysis of various policy measures and strategies at the national level to tackle main regulatory, ecological, MSP and supply chain challenges.

Challenge	Country: France
Regulatory and administrative	The ESSOC law (Law on a State at the service of a trusting society) adopted in 2018, and its application decree on authorization procedures for ORE installations have established the competitive dialogue for awarding ORE projects and have created the "envelope permit" for more flexibility in OWF design projects (for instance a change in the number/power of OW turbines).
	The ASAP Law in 2020 framed the mutualization of public consultations for the development of multiple offshore wind projects on the same maritime seafront over several years (example of the two OWFs (1GW and up to 2GW) off Oleron island). The ASAP application decree published in March 2021 has reduced steps in lawsuits on ORE involving exclusively the Council of State.
	The law for the Acceleration of Renewable Energy has been adopted in March 2023 provides a new regulatory and institutional framework will support the scaling-up of ORE deployment (50 OWFs and 40 GW by 2050). The law aims to streamline administrative procedures and reduce bureaucracy. It re-enacts the single permit rule, which now also applies to projects located in the exclusive economic zone. The law allows for the merging of two different public consultation processes into a single consultation be set up for both ORE projects siting and the elaboration of MSP documents. Besides, this single public consultation could concern more than one maritime seafront.
Ecological	The ECUME Working Group established in 2018 has launched in 2022 three major studies on the cumulative impacts generated by the seven OWF already authorized in the Northeast Atlantic arc (collision risk, submarine noise).
	In August 2021, a governmental fund of 50 million € has been allocated to finance an observatory of the marine environment and enhance the

[71] Regulation (EU) 2022/869 of the European Parliament and of the Council of 30 May 2022 on guidelines for trans-European energy infrastructure, amending Regulations (EC) No 715/2009, (EU) 2019/942 and (EU) 2019/943 and Directives 2009/73/EC and (EU) 2019/944, and repealing Regulation (EU) No 347/2013.

[72] COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future.

	monitoring of OWFs effects. Other state fundings are also granted for the creation of an observatory of OWFs socio-economic impacts to be launched in early 2023.
Economic and financial	Economic and financial measures aim at encouraging investment through incentives and derisking investments in ORE technologies. These incentives may consist of : 1) a fixed feed-in-tariff; 2) a new procedure of competitive dialogue (Energy transition Law, 2015; ASAP Law, 2020); 3) the Contract for Difference support mechanism; and 4) private investments and fundraising (PACTE Law, 2019; Acceleration of ORE Law, 2023).
MSP/Multi-use	When it is possible and secure, some activities (maritime navigation fishing, tourism…) are allowed inside OWFs areas, after a concertation between relevant stakeholders (Prefectoral Decision on the regulation of maritime activities around the Saint Nazaire offshore wind farm, December 2022). Some areas are delineated for habitats and marine environment protection, where specific conditions for possible co-location with ORE are required (Law and Order of 2001, with their application decrees in 2001 concerning the implementation of the European Directives Frameworks on Birds and Habitats). The compatibility between coastline "remarkable areas" and OWFs needs to be studied and validated at the local scale, on a case-by-case basis, both for OWF area (visual and aesthetic impacts) and landing (electrical sub-stations) (Coastline Law, 1986; Environment Code).
Supply Chain	A deal signed in 2022 between the government and ORE sector aims at achieving a local content of 50% by 2035 and allocate 2GW/year via tenders (Pacte éolien en mer, Ministry for Energy Transition, March 2022).
	The Atlantic is a strategic region for the ORE supply chain in France: blades manufacture in Cherbourg as well as Siemens Gamesa blades and nacelles manufacture; GE Renewable Energy assembly plant in Saint Nazaire and GE world headquarters in Nantes; Les Chantiers de l'Atlantique factory in Saint Nazaire for OWF foundations and electrical substations; the Brest harbour wing dedicated to ORE assembly. All these facilities are the result of a strong national and regional policy that underpin the value chain. France has become a major industrial hub (for the manufacture of turbines and nacelles), representing one third of European industrial capacity.
Challenge	**Country: Ireland**
Regulatory and administrative	The Irish government has established in 2021 a legislative framework of a new streamlined development consent process for activities in the maritime area including offshore renewable energy projects (framework approved under the Maritime Area Planning bill). This legal structure is expected to be approved in the Policy Statement on the Framework for Ireland's Offshore Electricity Transmission System (n.d.), which establishes periodic RESS auctions for offshore wind energy, setting the objective of 5GW in 2030. The government has launched, through its Sustainable Energy Authority of Ireland (SEAI), the Offshore Renewable Energy Development Plan II (OREDP II) to develop a long-term plan to take advantage of a potential of at least 30 GW of floating wind off the Atlantic coast.
Ecological	Strategic Environmental Assessment (SEA) services are used for the creation of a Strategic Environmental Assessment (SEA) and an

	Appropriate Assessment (AA) as applicable for the Offshore Renewable Energy Development Plan 2 (OREDP II), in compliance with European Directives on Environmental assessment, Habitats and Birds. It is anticipated that the draft plan and supporting environmental reports will be published for consultation in the latter half of 2022.
Economic and financial	In 2019, the Renewable Electricity Support Scheme (RESS) has been approved andand is set to finance renewable projects in Ireland from 2020 to 2025 with €1.4 billion for the 5 years. The Sustainable Energy Authority of Ireland (SEAI) has developed the National Energy Research Development and Demonstration (RD&D) Funding Programme 2022. This programme notably focuses on 1) the deployment in the Irish marketplace of competitive energy-related ORE products, processes and systems; 2) the support solutions that enable technical and other barriers to energy market uptake to be overcome.
MSP/Multi-use	MSP is directly dependent of the Department of Housing, Local Government and Heritage and the Department of the Environment, Climate and Communications to ensure an integrated marine spatial management strategy. The Sustainable Energy Authority of Ireland (SEAI) also supports innovation Programmes related to a better integration and sustainability of energies communities in the ORE sector.
Supply Chain and Grid Planning	The plan of the Department of the Environment, Climate, and Communications (DECC) contains a group of three main phases and policies (2020-2030) related to both supply chain and grid planning. The policies are designed to update the Ireland's Offshore Electricity Transmission System from the current decentralized offshore transmission system model to a centralized model and provide ORE the tools to develop projects. Irish government planning addresses the creation of the Celtic Interconnector Project, to create an electrical interconnection between France (Finistère) and Ireland (East Cork) to allow the exchange of electricity between the two countries. It is being developed by EirGrid, the electricity transmission system operator in Ireland, and its French counterpart, RTE (Réseau de Transport d'Électricité). Recognised as a Project of Common Interest (PCI) by the European Union, the Celtic Interconnector project responds to European challenges regarding streamlined supply chain processes in ORE transition towards a low-carbon electricity mix.

Challenge	Country: Portugal
Regulatory and administrative	In April 2022, Portugal has published the decree-law (N°30-A/2022) to create a temporary exceptional scheme for simplifying administrative procedures to accelerate the production of energy from renewable sources. In October 2022, the publication of a second decree-law (n°72/2022) continued the administrative simplification effort. The second decree-law now covers the procedures for the prior control of urban planning operations. It aims to adapt these procedures to simplify the operations for the installation renewable energy production capacities and the production of hydrogen by water electrolysis.

Ecological	During the application procedure for the titles of utilisation of maritime space (TUPEMs), the ORE promoter must consult relevant public entities, including environmental agencies, on the potential ecological impacts of its projects and the associated mitigation measures.
Economic and financial	In January 2022, Portugal has approved a new legislation (Decree-Law n°15/2022) that provides for the elimination of guaranteed remuneration schemes as opposed to the general remuneration scheme, opting to establish a single remuneration scheme based on the price freely determined on the market. Notwithstanding, under the provisions of the European Union directives, recovery of investment costs for renewable energy installations can be granted, as long as competitive procedures are carried out.
MSP/Multi-use	There are some requirements associated to the attribution of Titles of utilisation of maritime space (TUPEMs), mandatory for the licencing procedure for offshore electricity production in Portugal. These requirements aim to improve the co-existence of socio-economic activities at sea, involving as much as possible public entities, the public and stakeholders in consultation processes to define the MSP/multi-use terms. In this regard, during the period of the public consultation, an identical request for a TUPEM may arise, leading to a tender procedure.
Supply Chain	In 2017, the Portuguese government has ratified a Strategic Industrial plan for Ocean Renewable Energy, (EI-ERO). The plan articulates over three pillars: 1) Attract R&D and pilot projects to bring Innovation; 2) Accelerate exports of ocean renewable energy technologies by strengthening national business capacity and promoting innovative products and services; 3) Implement initiatives to enhance investments in Ocean Renewable Energy.

Challenge	Country: **Spain**
Regulatory and administrative	The Roadmap for Offshore Wind and Marine Energy in Spain, approved in December 2021, stresses that a clear and predictable regulatory framework for the deployment of offshore renewables is a high priority. The Roadmap also provided the adaptation of the administrative framework for the authorization of offshore renewable installation to streamline a permitting process that could take up to 5 years. In June 2022 the Ministry for Ecological Transition and the Demographic Challenge has coordinated a public consultation prior to the design of the regulatory framework for the development of offshore and marine energy installations. The approval of new farms is currently suspended as per Royal Decree and Law 12/2021, until the adoption of this new regulatory framework. Exceptions are made for deployments in infrastructures for the testing, demonstration and validation of prototypes and new technologies. Spain has three such infrastructures, in Canary Islands (PLOCAN), Basque Country (BiMEP), and Galicia (Punta Langosteira). ORE projects in Spain will require thorough environmental impact assessment and strategy for contributing to a more sustainable marine environment. The EIA Law (21/2013, 9 December) establishes a period of no more than 6 months to obtain the environmental authorization for marine electricity production. It is expected that EIA

	regulations will be updated and streamlined with the rest of the consenting process in the coming years.
Ecological	The Roadmap emphasizes the need to use marine renewable infrastructure to better monitor the marine environment and ecosystem health. Regulations for noise during construction are being considered, with the objective of adopting best practices in the sector.
Economic and financial	Spain has important assets to obtain large economic benefits from accelerated deployments of marine renewables. This includes a supply chain that is already successful in delivering marine structures and electrical equipment for offshore wind in the North Sea, as well as world-leading utilities in the offshore wind sector and renewables.
MSP/Multi-use	The Marine Spatial Planning framework (POEM) is being updated, with one explicit objective to facilitate the acceleration of offshore renewables deployment and its compatibility with traditional and new users of the maritime space. An extensive public consultation that is in the process of being reflected in the updated planning of the marine space was conducted in June 2022. The Ministry of Ecological Transition and the Demographic Challenge is leading this effort. The Roadmap also updated regulations and administration of marine energy, including the definition and approval of zoning for the development of offshore wind farms in the POEM.
Supply Chain	The supply chain for offshore wind in Spain is already highly competitive in supplying offshore structures and electrical equipment for projects in other countries. The Roadmap does identify a need to update port infrastructure to support deployment goals, with an initial estimation of 500 million to 1 billion € of needed extensions. The government is expected to open tenders for applying parts of the (COVID) Recovery Funds for the manufacturing of a marine structure for offshore wind (PERTE Naval) and for the development of test sites (BiMEP, PLOCAN, Punta Langosteira) and innovative prototypes (PERTE Renovables).

5. IDENTIFICATION OF PRIME AREAS FOR OFFSHORE DEVELOPMENT

This chapter presents the methods for, and results from, the selection and ranking of prime areas for offshore development, which will be performed on and within the macro-scale areas and sites pre-selected in Chapter 1, more specifically, in Section 1.2. The preliminary selection of areas in Chapter 1 may be seen as the result of a first layer of analysis, a first sieve, which is complemented with a second layer, the identification of prime areas, in the present Chapter. The results of the LCOE analysis carried out in Chapter 2 are used here as one of the criteria for the selection of prime areas. Other criteria follow from the analysis of non-technical constraints in Chapter 1, in particular, in Section 1.2.1.3. With respect to Chapter 3, its conclusions indicate that a radial connection is associated to lower CAPEX and OPEX than the hybrid alternatives – irrespective of the area in question. In other words, the conclusions apply similarly to the different study areas, and therefore should not alter the selection of prime areas for future development.

5.1.1. Methods

The approach used in this analysis is the multi-criteria linear analysis, which evaluates multiple conflicting interdependent variables assigning weights to each. Five main phases may be differentiated in this approach:

- Identification of relevant criteria
- Exclusion zones
- Definition of variables
- AssignmentAssignment of weights
- Calculation of ranking indices and generation of maps

5.1.1.1 Identification of relevant criteria

The relevant criteria are of two types: the Levelised Cost of Energy (introduced in Chapter 2) and the non-technical constraints (discussed in Chapter 1, Section 1.2.1.3). Thus, based on the previous Chapters, the following criteria are considered:

- Levelized Cost of Energy (LCOE)
- Military areas
- Marine protected areas
- Fisheries
- High-intensity shipping lanes
- Oil and Gas platforms
- Communication cables

Of these criteria, the first four (1 to 4) are accounted for through a linear combination of variables defined *ad hoc* in the present study, which yields an index. The method is described in detail in Section 5.1.1.3. By contrast, the last three criteria (5 to 7) are considered through the definition of exclusion zones, as described in Section 5.1.1.2, below.

5.1.1.2 Exclusion zones

The following activities give rise to exclusion zones, which are deemed incompatible with ORE exploitation for the purposes of the present study:

- High-intensity shipping lanes
- Oil and Gas platforms
- Communication cables

The authors are aware that the aforementioned incompatibility is a matter of debate, and their decision to classify these uses of the marine space as incompatible with offshore renewable energy may be revised in future in the light of new research. At present, however, due to the inconclusive evidence as to the prospects for their co-existence, an assumption of even partial compatibility would not appear warranted.

5.1.1.3 Definition of variables

To consider the first four criteria in Section 5.1.1.1 in a qunantitative manner, four variables are defined in this section, and four weighting coefficients in the next.

Levelised Cost of Energy
The corresponding variable is:

$$x_{LCOE}(i) = \frac{LCOE_{min}}{LCOE(i)}$$

where LCOE(i) is the value of the LCOE at area *i* and $LCOE_{min}$ is the minimum value of the LCOE in the entire Atlantic region considered in this work.

With this definition, $x_{LCOE}(i)$ = 1 if area *i* has the minimum possible value of the LCOE (of all the values in the Atlantic region considered), and $x_{LCOE}(i)$ = 0.5 if the LCOE at area *i* is twice as large as the $LCOE_{min}$.

Military zones
These areas are accounted for through a binary approach:

$$x_m(i) = \begin{cases} 1 & \text{if area } i \text{ is in a military zone,} \\ 0 & \text{otherwise.} \end{cases}$$

Marine protected zones
Marine protected areas included in the Natura2000 network are similarly taken into account through a binary approach:

$$x_n(i) = \begin{cases} 1 & \text{if area } i \text{ is in a Natura2000 protected zone,} \\ 0 & \text{otherwise.} \end{cases}$$

Fisheries
Fishing zones are considered through the following variable, which depends on the annual fishing hours from the EMODNet database[73]:

$$x_f(i) = \frac{FH(i)}{FH_{max}FHmax}$$

where $FH(i)$ is the number of fishing hours at area *i*, and FH_{max} is the maximum number of fishing hours at any zone in the entire Atlantic region considered. Thus, x_f may be seen as a nondimensional normalized indicator of the level of fishing activity: x_f = 1 at the area with maximum number of fishing hours, x_f = 0.5 at an area with half the maximum number of fishing hours, and x_f = 0 at an area with no fishing activity.

5.1.1.4 Assignment of weights

The next step of the multi-criteria analysis is the assignment of weighting coefficient to each criterion (to each variable defined in the previous section) for the calculation of the ranking index. At present there is no regulatory guidance on the assignment of such weights. The values chosen here (Table 5-1) are based on the authors' expert judgment. In future, research may shed new light on the selection of weights.

[73] https://www.emodnet-humanactivities.eu/search-results.php?dataname=Fishing+Intensity

TABLE 5-1 : WEIGHTING COEFFICIENTS ASSIGNED TO EACH CRITERION

Coefficient	Value
α_{LCOE}	100
α_m	-20
α_n	-25
α_f	-20

The positive weighting coefficient assigned to the LCOE variable (α_{LCOE}) combined with the definition of the variable itself (x_{LCOE}, see previous section) means that, the lower the LCOE, the greater the ranking index, caeteris paribus. Based on Table 5-1, the ranking index of the area with the minimum possible LCOE would have 100 points on that account.
The negative weighting coefficients assigned to the remaining variables (α_m, α_n, α_f) imply that these variables act as penalizing factors. The penalties are applied as follows. If the area in question is in a military zone (x_m = 1), 20 points are subtracted from the ranking index. Similarly, if the area is in a Nature2000 protected zone (x_n = 1), 25 points are subtracted from the ranking index. With respect to fishing areas, the penalization is not applied in a binary fashion (yes/no, 1 or 0) but through a variable (x_f) which takes into account the level of fishing intensity through the fishing hours per year. At an area where the number of annual fishing hours would be the maximum of the entire Atlantic region considered (x_f = 1), 20 points would be subtracted from the ranking index. At an area where the number of fishing hours would be half the maximum (x_f = 0.5), only 10 points would be subtracted.

5.1.1.5 Calculation of ranking index and generation of maps

The four criteria (1 to 4) in Section 5.1.1.1 are considered for the calculation of the ranking index. Each criterion is weighted by a certain coefficient, indicated in Table 5-1. The calculation is undertaken by means of Equation 30 :

EQUATION 30

$$R(i) = \alpha_{LCOE} x_{LCOE}(i) + \alpha_m x_m(i) + \alpha_n x_n(i) + \alpha_f x_f(i),$$

where R(i) is the value of the index at area *i*.

Based on Equation 7 and Table 5-1, the maximum possible value of the ranking index would be 100, which would correspond to an area with the minimum LCOE (x_{LCOE} = 1), no military zone (x_m = 0), no marine protected zone included in the Nature2000 network (x_n = 0) and no fishing activity (x_f = 0).
The greater the value of R(i), the better the area for offshore energy exploitation, caeteris paribus. Thus, the ranking index enables areas to be be classified according to their attractiveness for future development.

5.1.2. Results

As indicated, the ranking index obtained with the above method is on a 100-point scale. This quantitative classification allows a quick identification of the prime areas for the exploitation of the respective offshore energy resource: offshore wind, wave, solar PV and tidal stream.

For each technology, two scenarios have been considered, 2030 and 2050, based on the LCOE values predicted for 2030 and 2050 in Task 2. The differences between them, though minor, may still be relevant in the development of long-term ORE projects.

5.1.2.1 Offshore wind

Due its state of development, offshore wind energy is arguably the offshore renewable energy that can make the greatest contribution in the coming years to decarbonizing the energy supply. With the restrictions and exclusion zones considered, there remain several zones with high scores, which ought to be prioritized for development (Figure 86 and Figure 87).

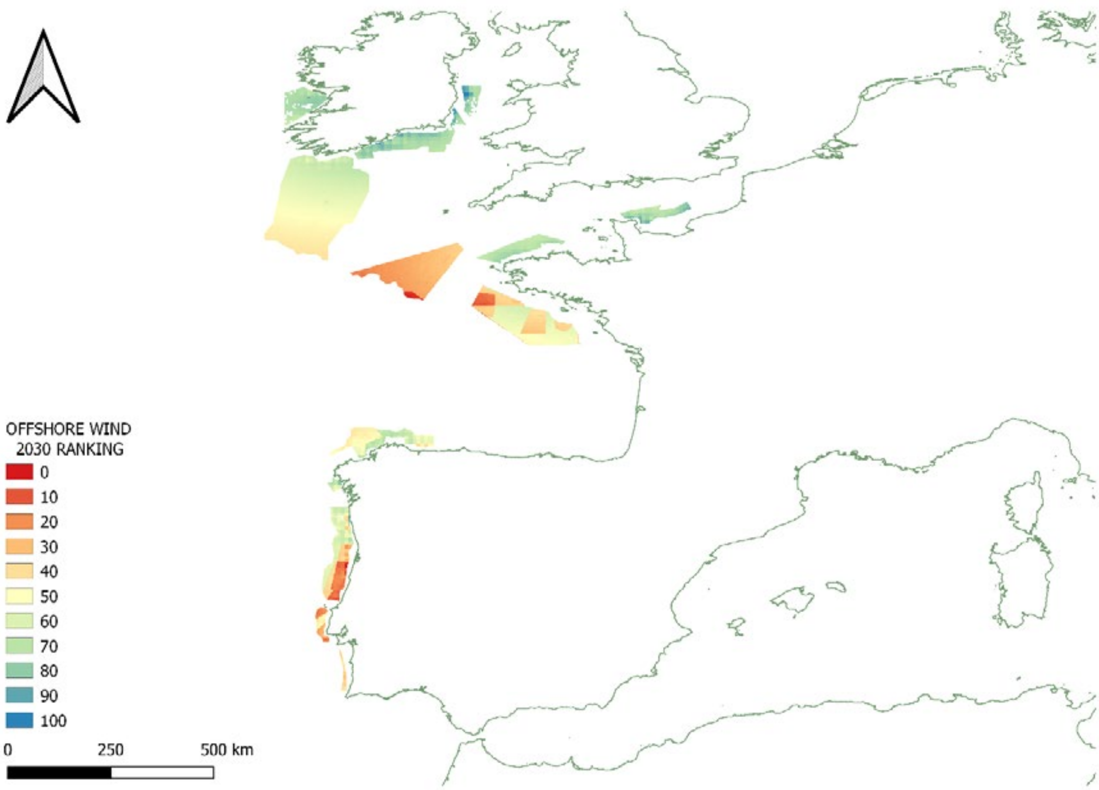

FIGURE 86 : OVERVIEW OF OFFSHORE WIND RANKING INDEX 2030 ALONG THE EUROPEAN ATLANTIC ARC

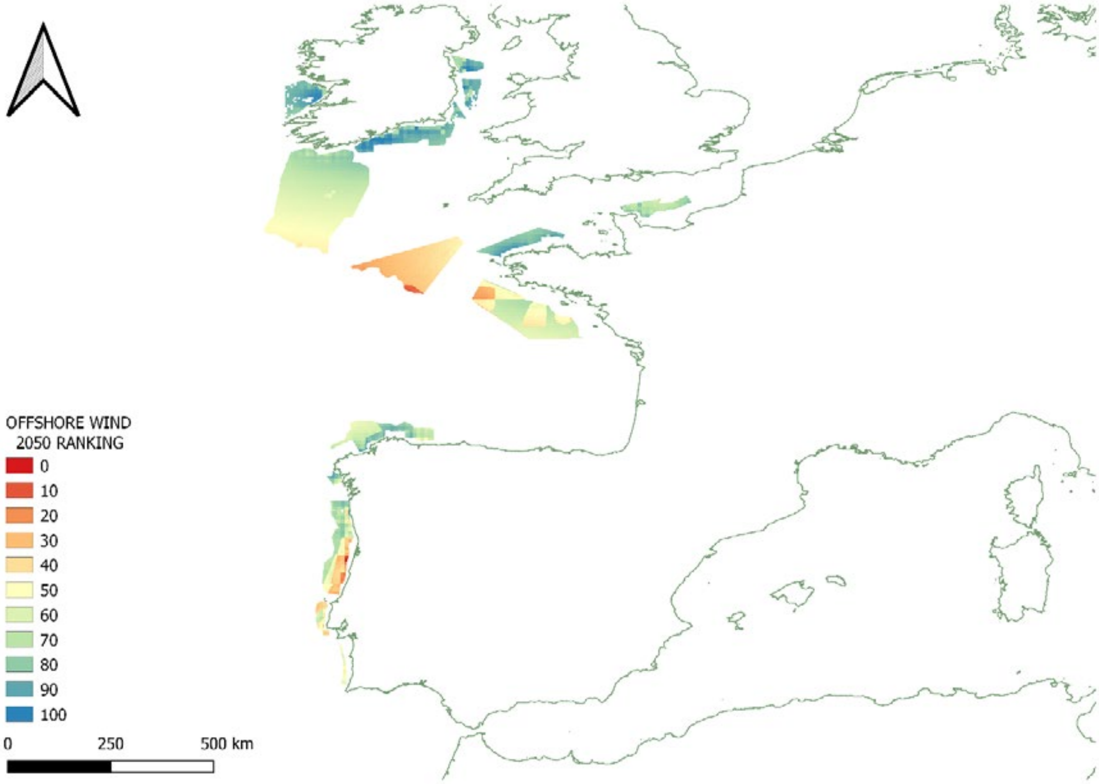

FIGURE 87 : OVERVIEW OF OFFSHORE WIND RANKING INDEX FOR 2050 ALONG THE EUROPEAN ATLANTIC ARC

The most suitable macro-areas are off Ireland, North of Brittany, Northwest Spain and North of Portugal.

More detailed maps of the areas close to Ireland are provided in Figure 88 (2030 scenario) and Figure 89 (2050 scenario). In this region, the areas off the Eastern and Southeastern coasts of Ireland are most promising, with nearshore values approaching 100, followed by part of the Western coast, with nearshore values of the order of 80. The highest-rated areas are located nearshore; notwithstanding, overall scores around Ireland are high, mostly due to the absence of restrictions. The 2050 map (Figure 89) presents higher overall scores due to the reduction in the LCOE. Scores are of the order of 80 even off the Southern coast. These results confirm the substantial potential of Ireland for the development of Offshore Wind projects.

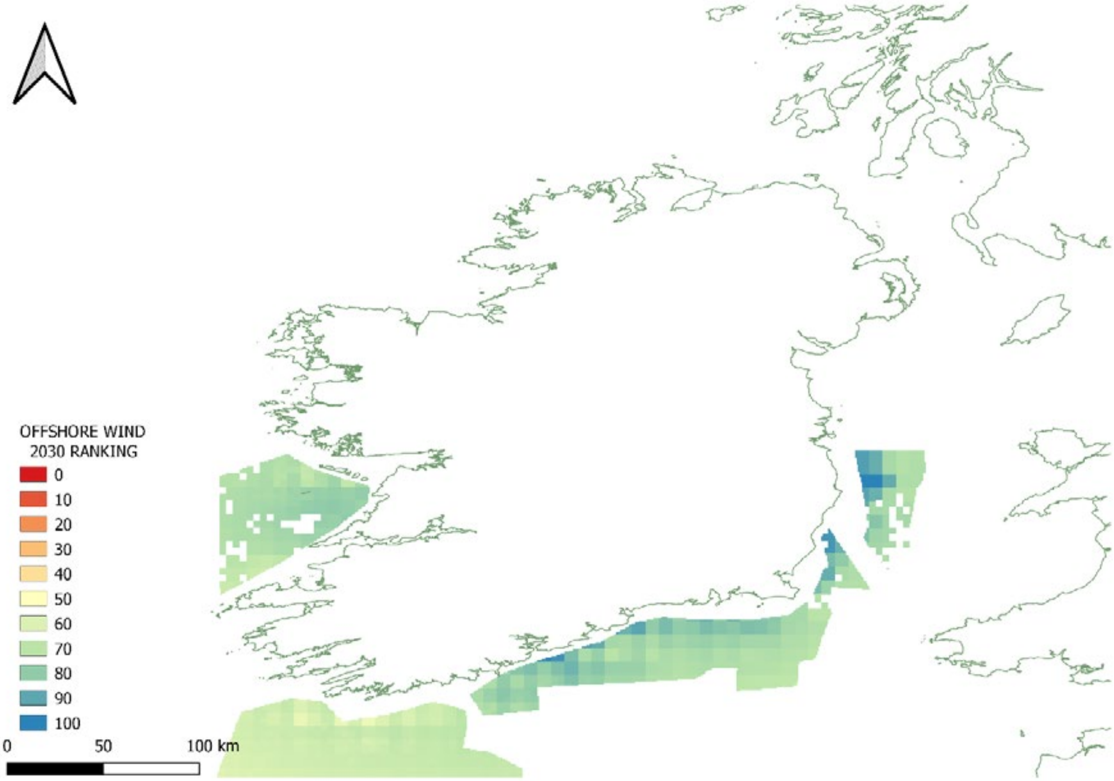

FIGURE 88 : OFFSHORE WIND RANKING INDEX FOR 2030 OFF IRELAND

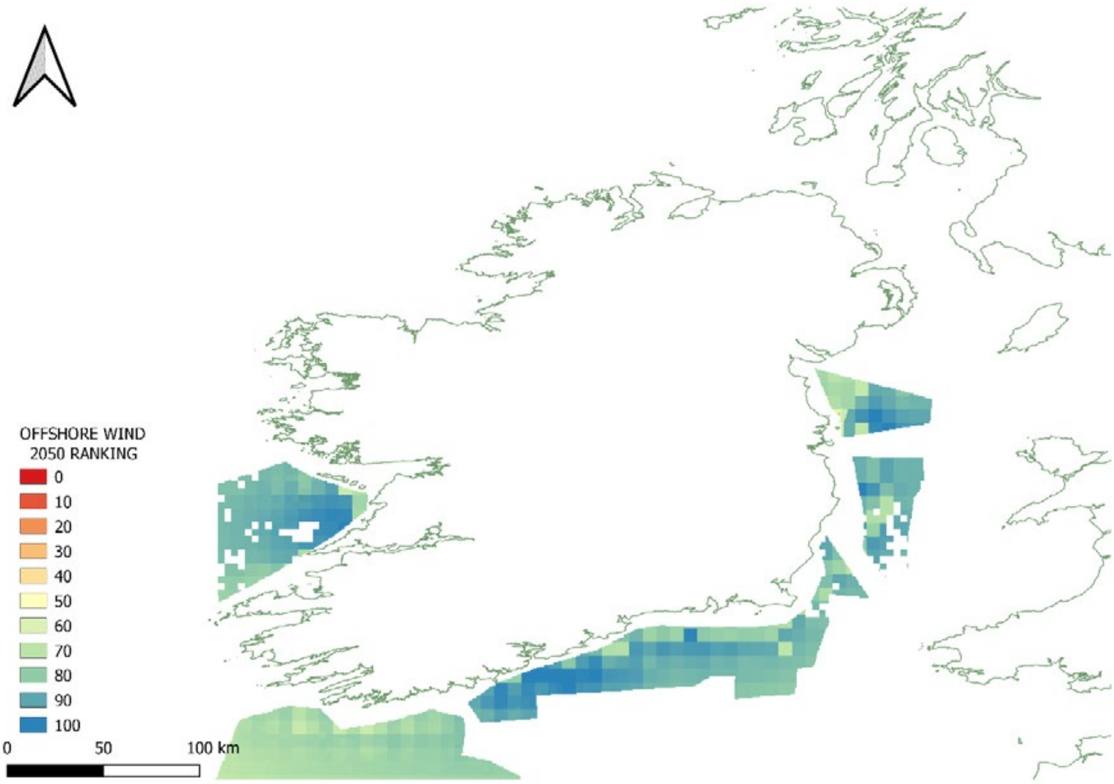

FIGURE 89 : OFFSHORE WIND RANKING INDEX FOR 2050 OFF IRELAND

Some areas off Western France (Figure 90 and Figure 91 for scenarios 2030 and 2050, respectively) are penalized by the presence of military and nature protected areas, as well as by intense shipping traffic and fishing activity. Therefore, scores tend to be lower than in Northern France, where certain areas off Northwestern Brittany and Normandy have scores in the 70-90 range. In the 2050 scenario (Figure 91) part of the Northwestern Brittany area presents scores above 90.

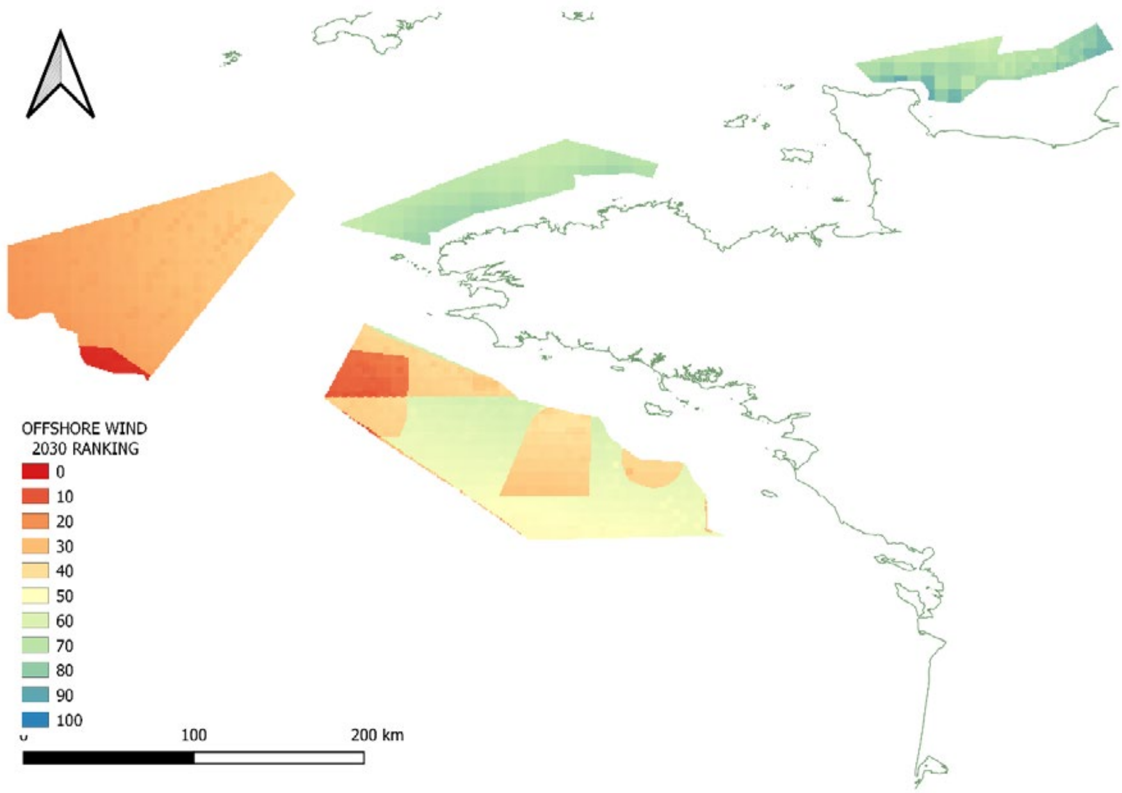

FIGURE 90 : OFFSHORE WIND RANKING INDEX FOR 2030 OFFSHORE FRANCE

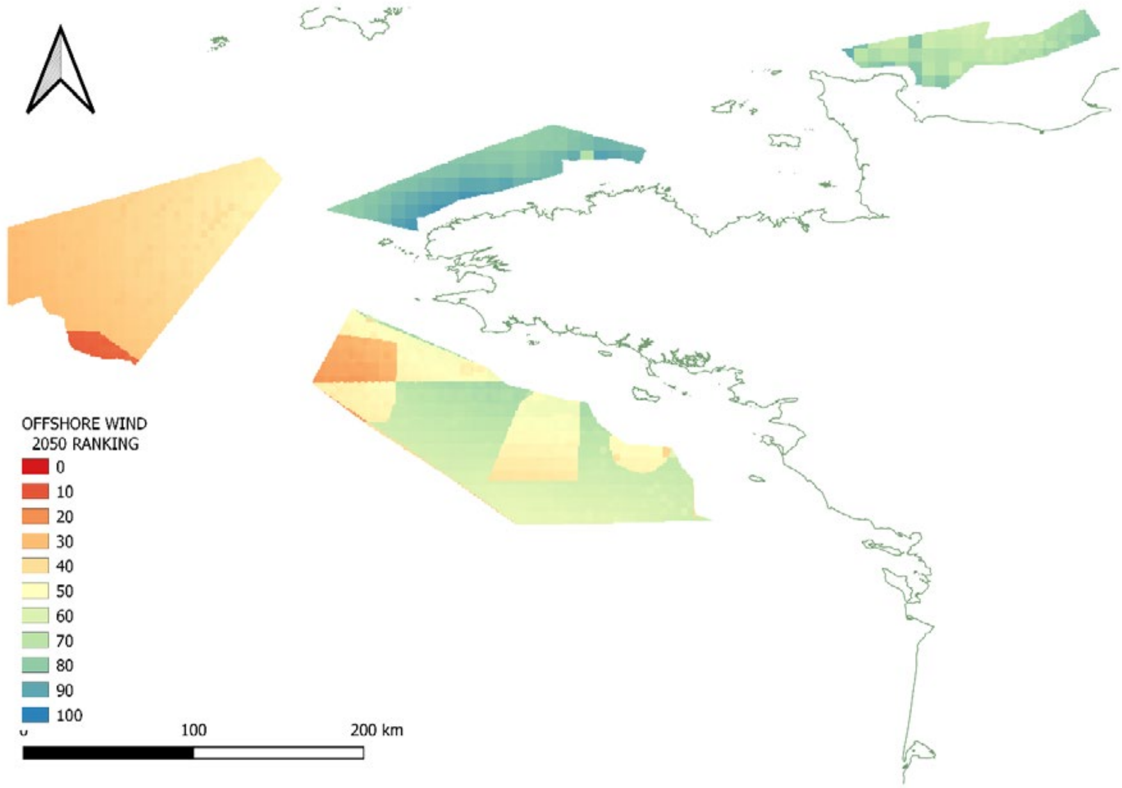

FIGURE 91 : OFFSHORE WIND RANKING INDEX FOR 2050 OFFSHORE FRANCE

For the Iberian Peninsula (Figure 92 and Figure 93), several high-scoring areas occur off the Northern coast of Portugal and the Galician arc (Nortwestern Spain). The presence of military zones, mainly in the South of Portugal, and marine protected areas, primarily along part of the Galician coast, contributes to reducing the scores of the respective areas. Continuing with the trend seen in the other zones, scores increase in the 2050 scenario, with values around 80-90 in many areas.

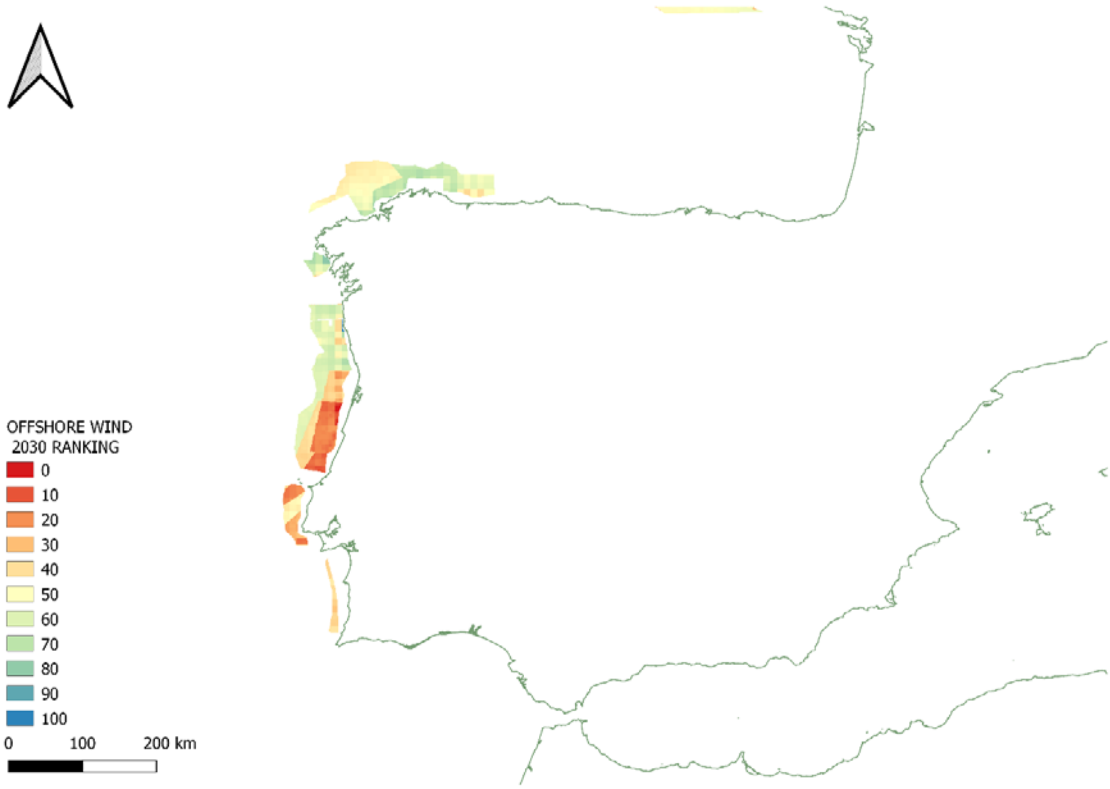

FIGURE 92 : OFFSHORE WIND RANKING INDEX FOR 2030 OFFSHORE THE IBERIAN PENINSULA

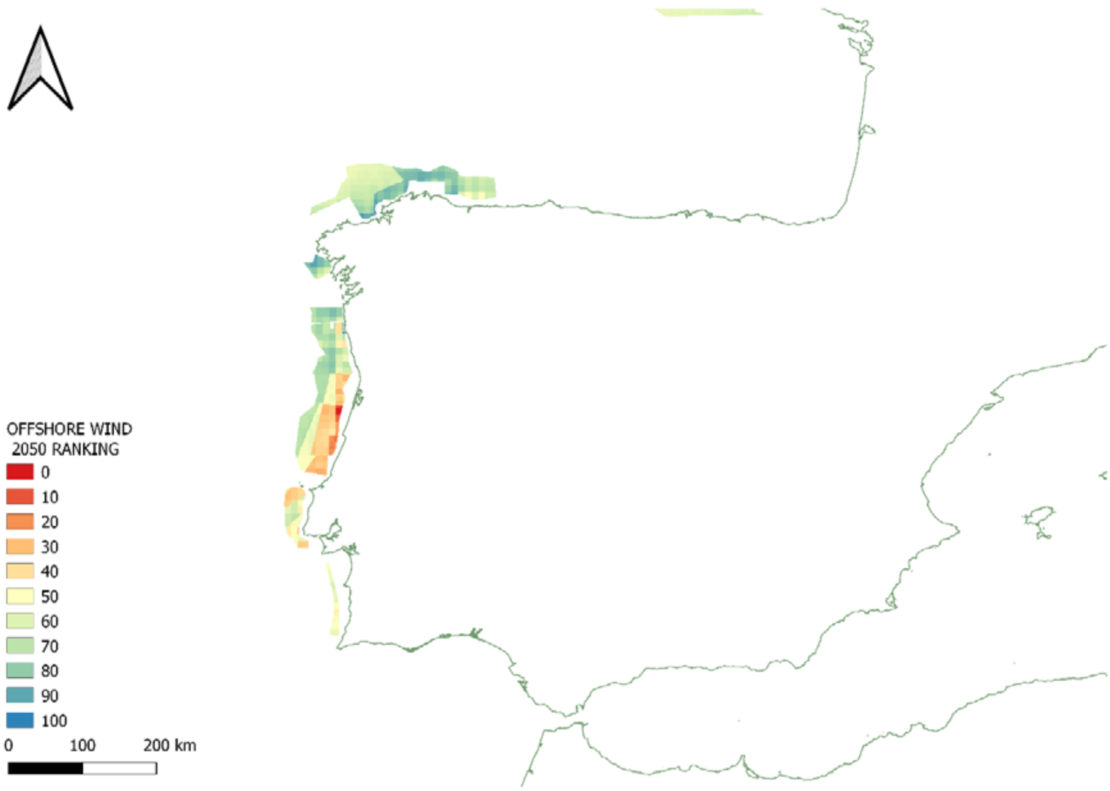

FIGURE 93 : OFFSHORE WIND RANKING INDEX FOR 2050 OFFSHORE THE IBERIAN PENINSULA

5.1.2.2 Wave energy

The wave energy resource in Atlantic Europe is vast, as discussed in previous chapters. The ranking of the selected areas is presented in the overview maps, Figure 94 and Figure 95 for 2030 and 2050, respectively. The overview maps show that primary areas for waves are located in Northern Portugal, Northwestern Spain and Northwestern France. West of France and Central Portugal are possibly more constrained.

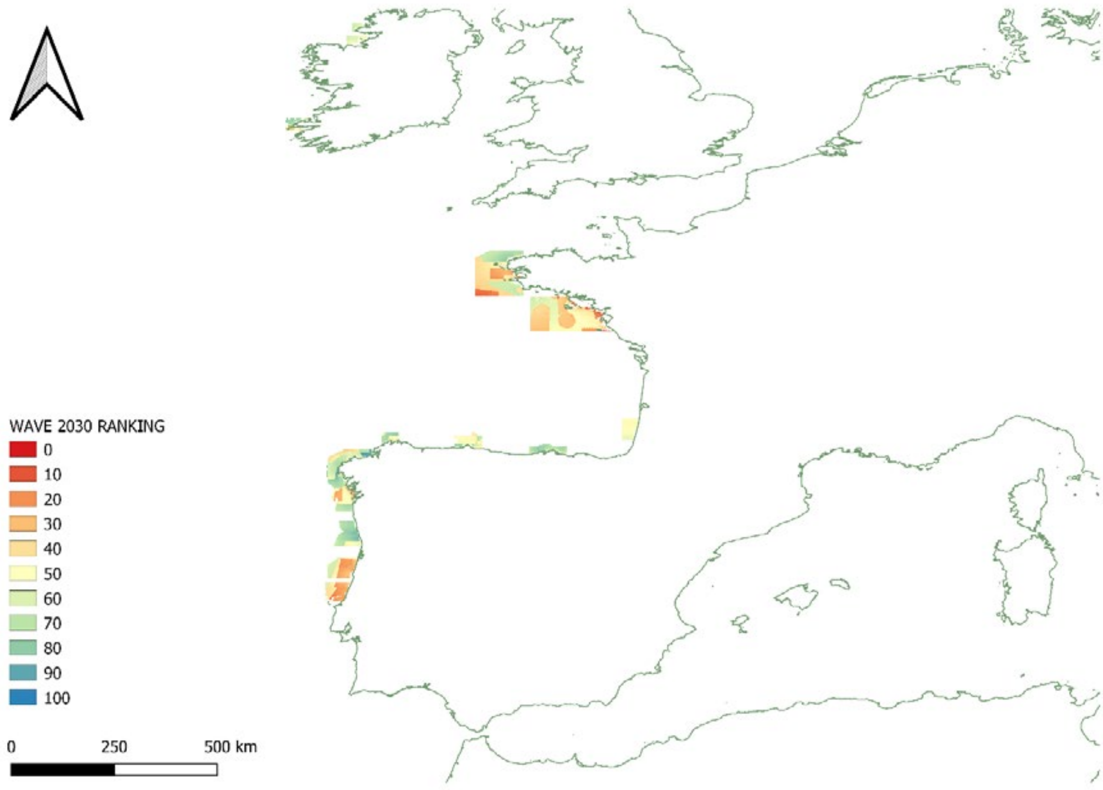

FIGURE 94 : OVERVIEW OF THE WAVE ENERGY RANKING INDEX FOR 2030 ALONG THE EUROPEAN ATLANTIC ARC

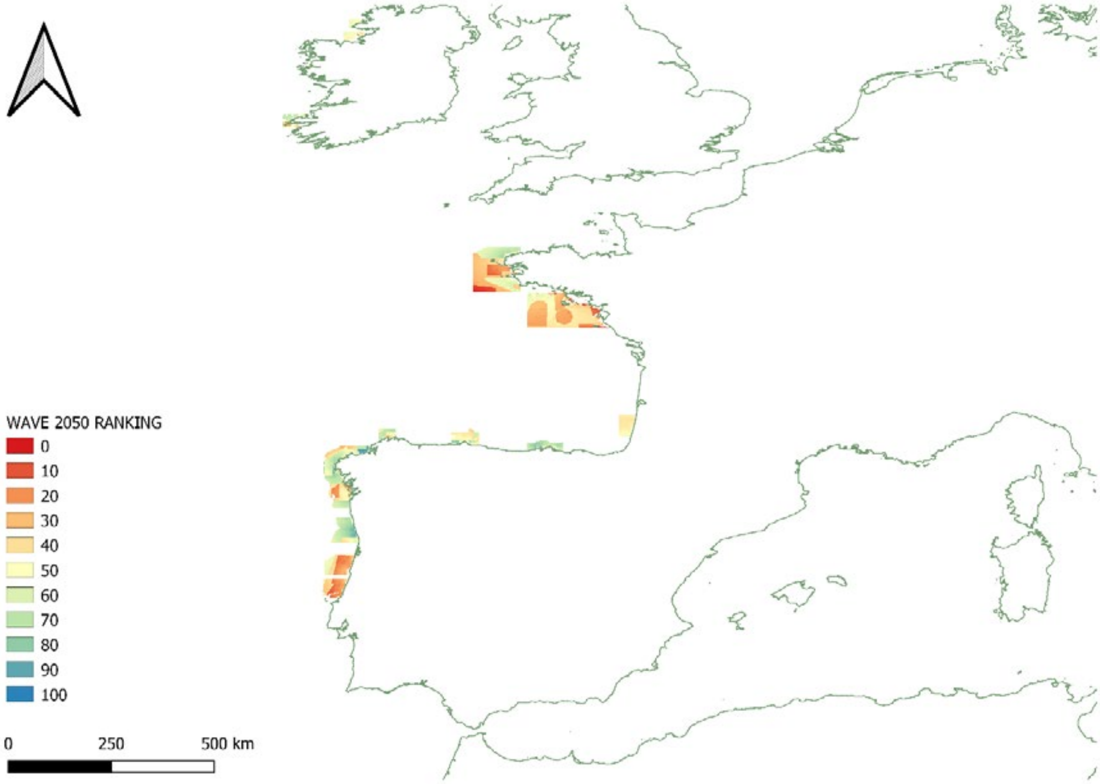

FIGURE 95 : OVERVIEW OF THE WAVE ENERGY RANKING INDEX FOR 2050 ALONG THE EUROPEAN ATLANTIC ARC

Figure 96 and Figure 97 present the results for Ireland. Some areas in the Southwest obtain high ranking values, in the top quartile. Their ranking decreases slightly in the 2050 scenario (Figure 97).

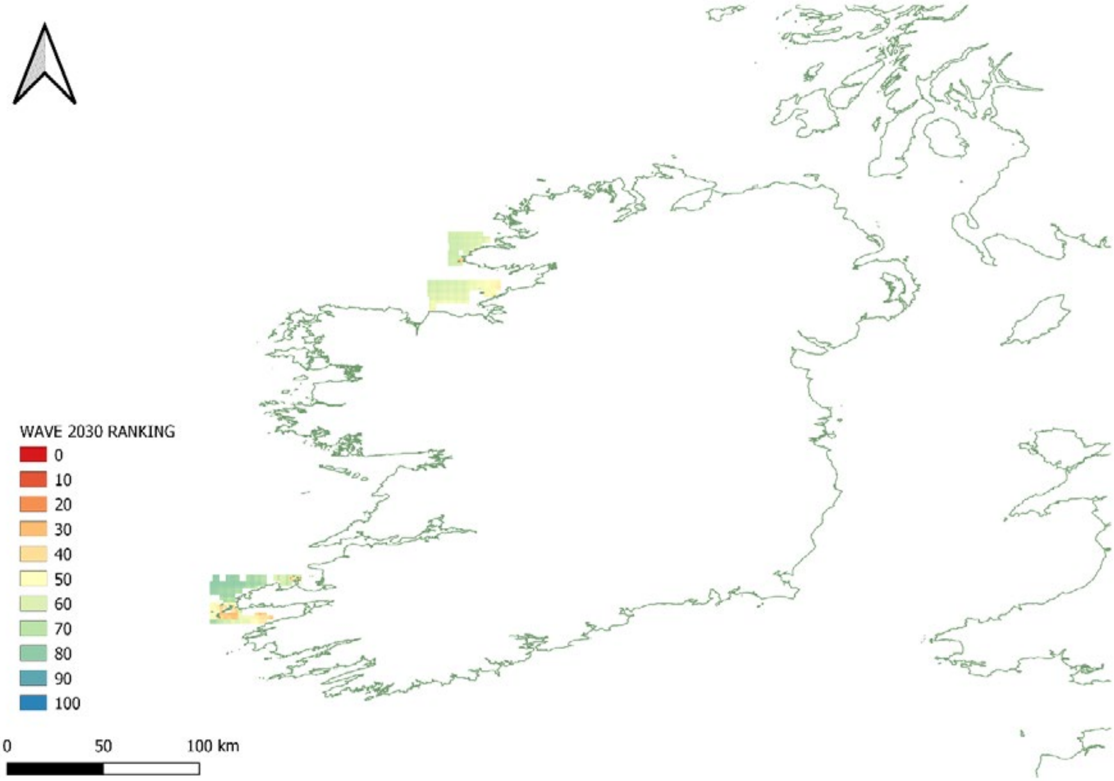

FIGURE 96 : WAVE ENERGY RANKING INDEX FOR 2030 OFFSHORE IRELAND

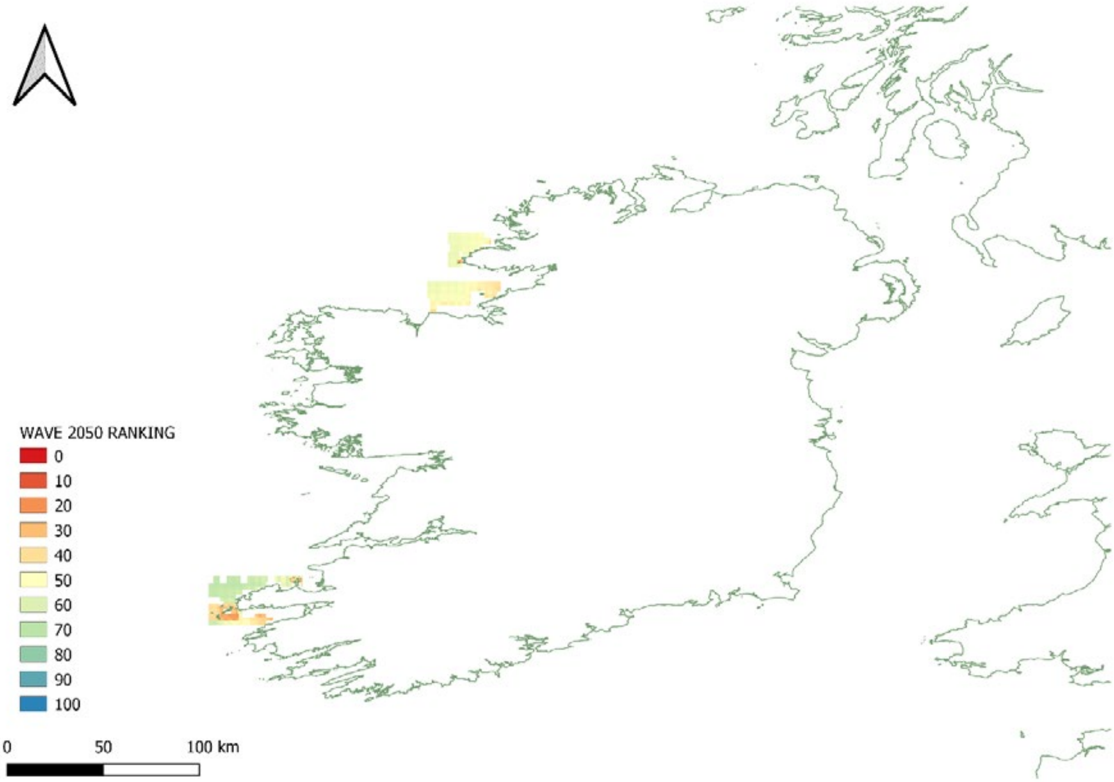

FIGURE 97 : WAVE ENERGY RANKING INDEX FOR 2050 OFFSHORE IRELAND

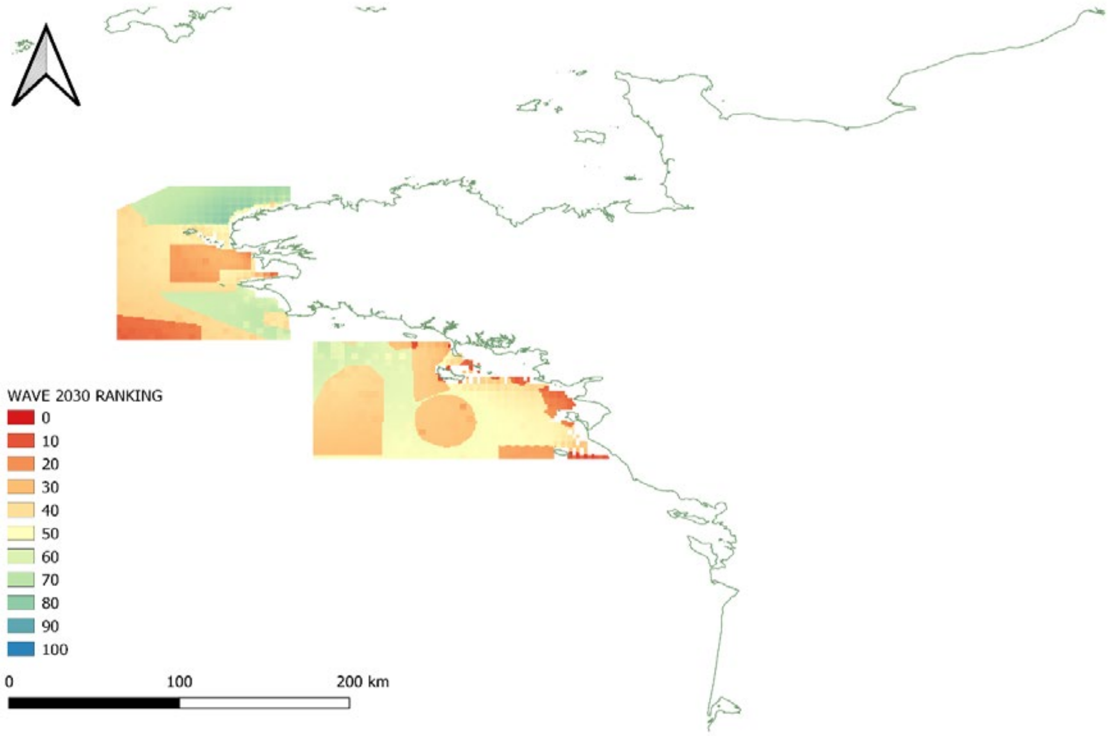

FIGURE 98 : WAVE ENERGY RANKING INDEX FOR 2030 OFFSHORE FRANCE

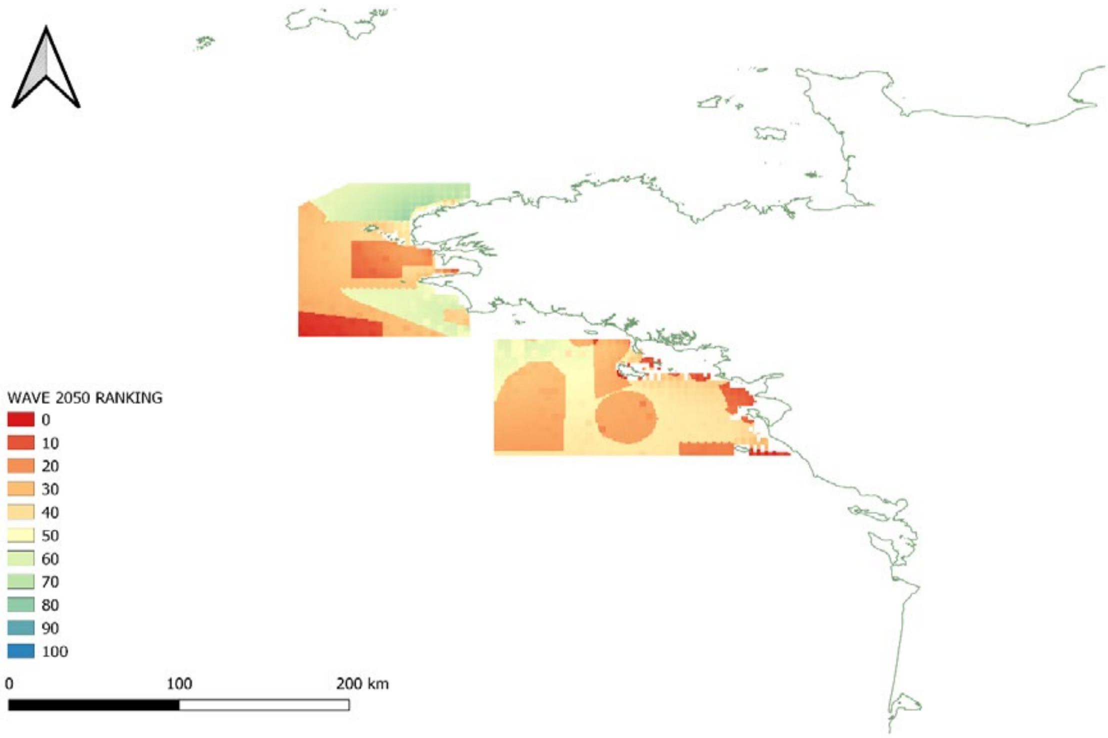

FIGURE 99 : WAVE ENERGY RANKING INDEX FOR 2050 OFFSHORE FRANCE

The results for France are presented in Figure 98 and Figure 99 for 2030 and 2050, respectively. The presence of large military and marine protected zones causes a large part of the Western French coast to be non-eligible, leaving the Northwest as the only available zone, where a large area can be exploited. Within that area, Northwestern Brittany is particularly interesting. The score of these areas decreases generally in the 2050 analysis relative to 2030.

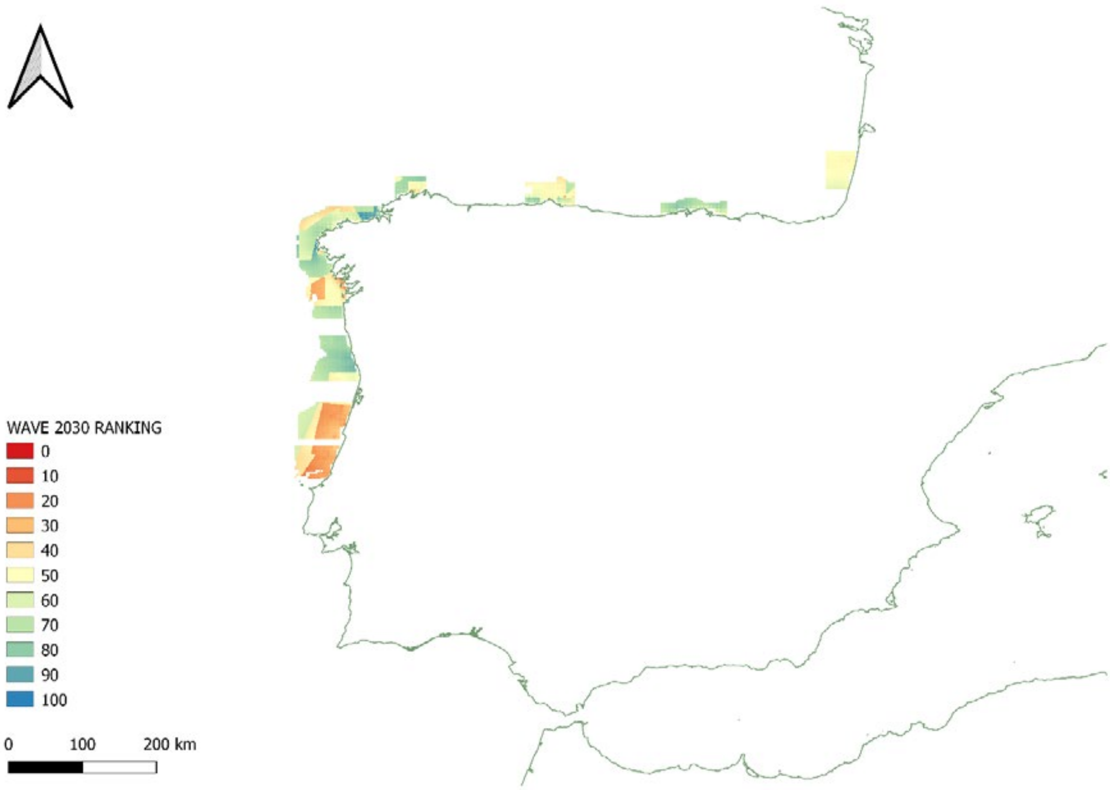

FIGURE 100 : WAVE ENERGY RANKING INDEX FOR 2030 OFFSHORE THE IBERIAN PENINSULA

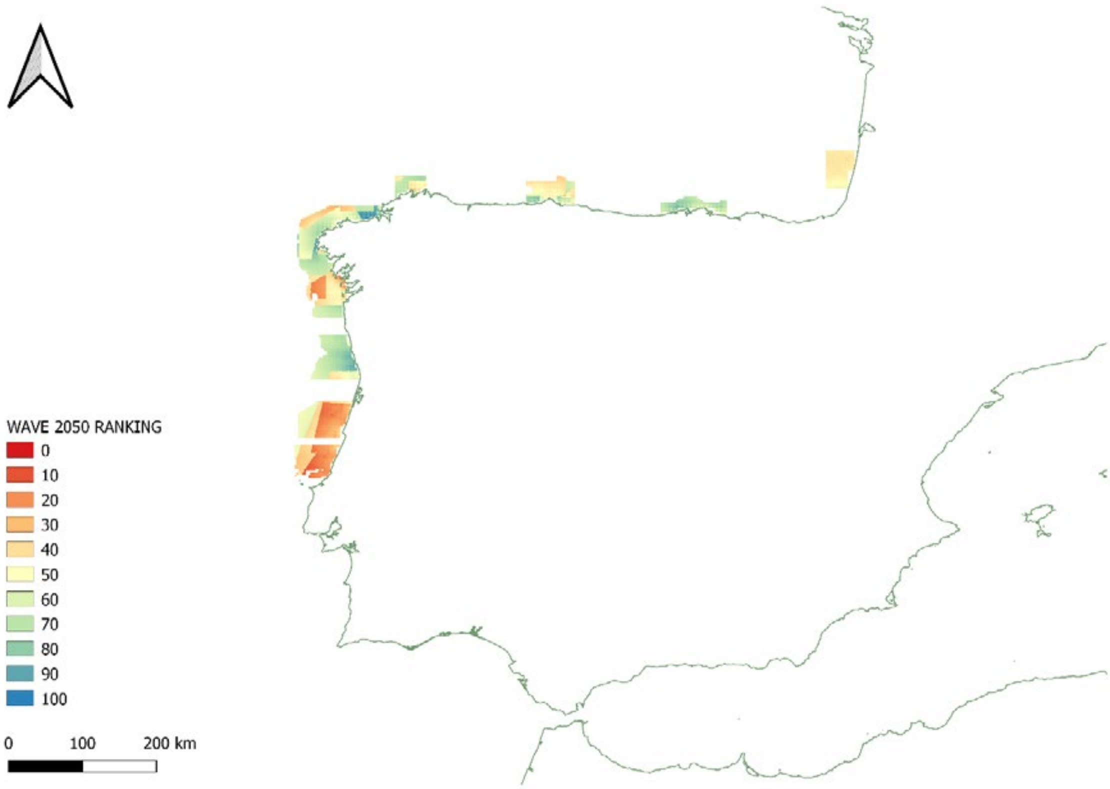

FIGURE 101 : WAVE ENERGY RANKING INDEX FOR 2050 OFFSHORE THE IBERIAN PENINSULA

The results for the Iberian Peninsula are presented in Figure 100 and Figure 101 for 2030 and 2050, respectively. Together with the Irish zone, this is the most promising zone for both scenarios, with suitable areas both along the Spanish and the Northern Portuguese coasts. Like the French areas, Southern Portuguese areas are highly restricted and less likely to be exploited.

5.1.2.3 Floating solar photovoltaics

Floating solar technologies have a lot many possibilities due to the rapid development of this technology and its ease of installation. The overview maps are presented in Figures 17 and 18 for 2030 and 2050, respectively.

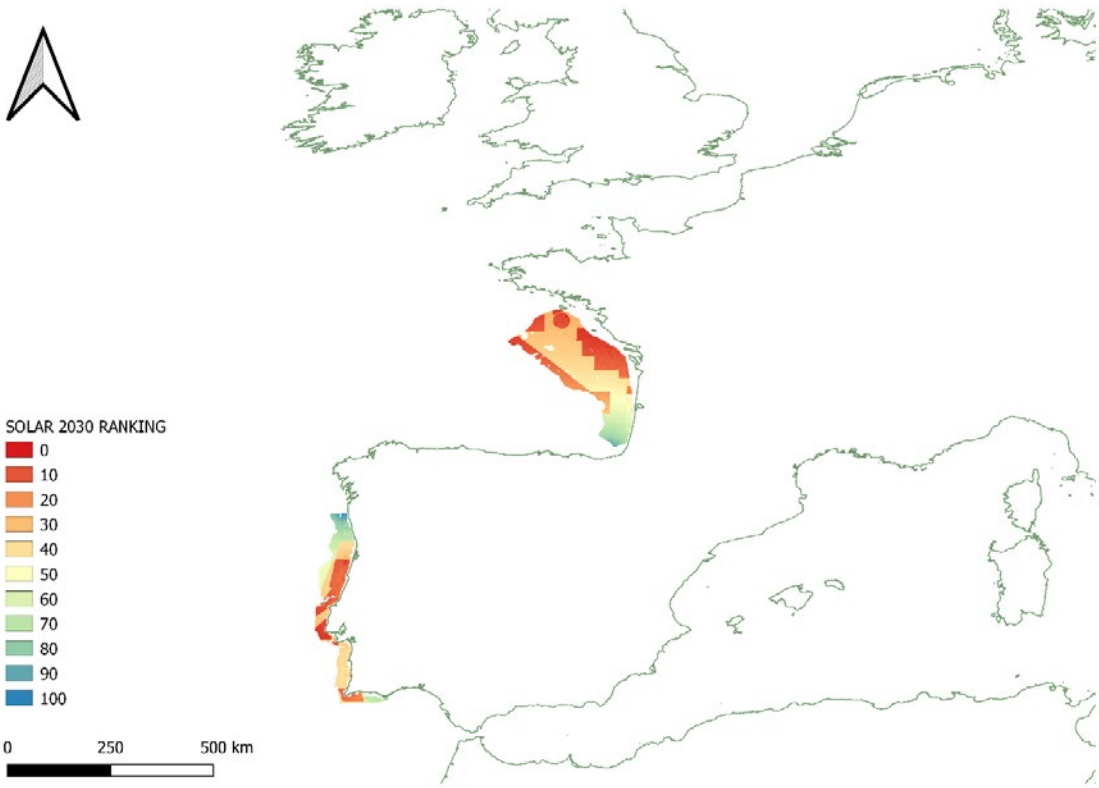

FIGURE 102 : OVERVIEW OF THE FLOATING SOLAR PHOTOVOLTAICS RANKING INDEX FOR 2030 ALONG THE EUROPEAN ATLANTIC ARC

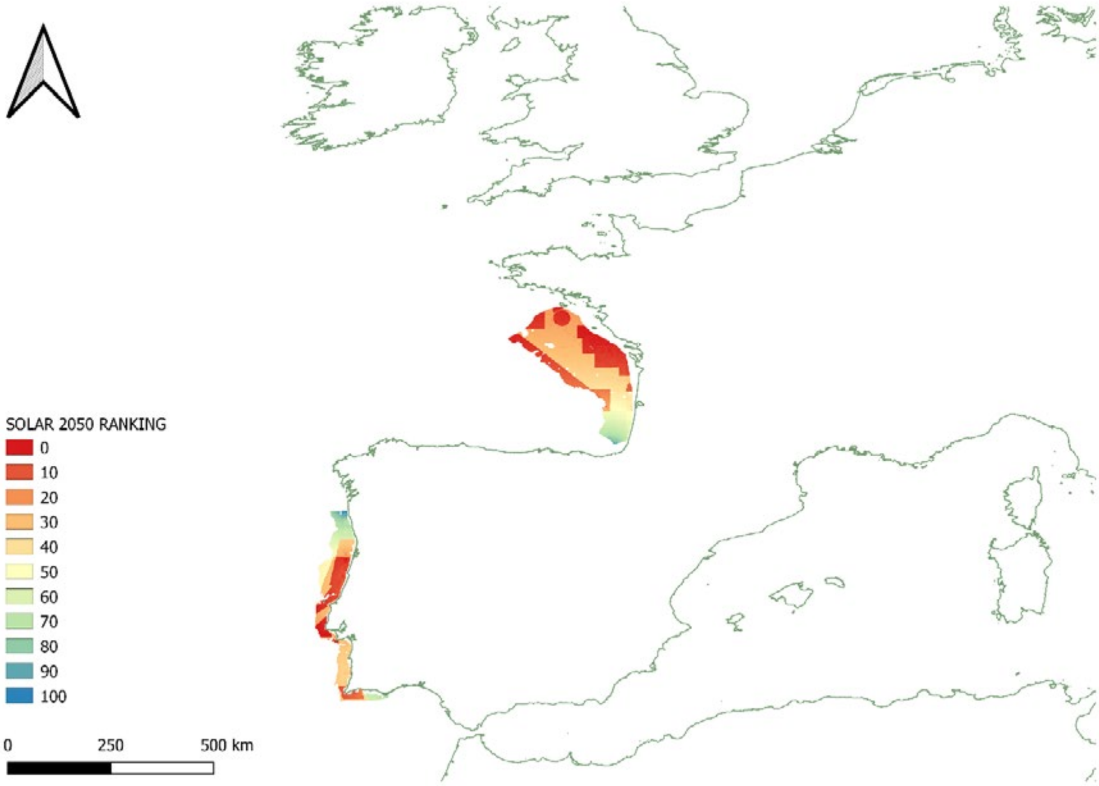

FIGURE 103 : OVERVIEW OF THE FLOATING SOLAR PHOTOVOLTAICS RANKING INDEX FOR 2050 ALONG THE EUROPEAN ATLANTIC ARC

As in the case of the other technologies, restrictions lead to some areas not being exploitable. Unlike the other technologies, the resource increases towards the south, resulting in some interesting areas as will be seen in the detail maps. The difference between scenarios is mostly based on a reduction in the LCOE in the most restricted areas.

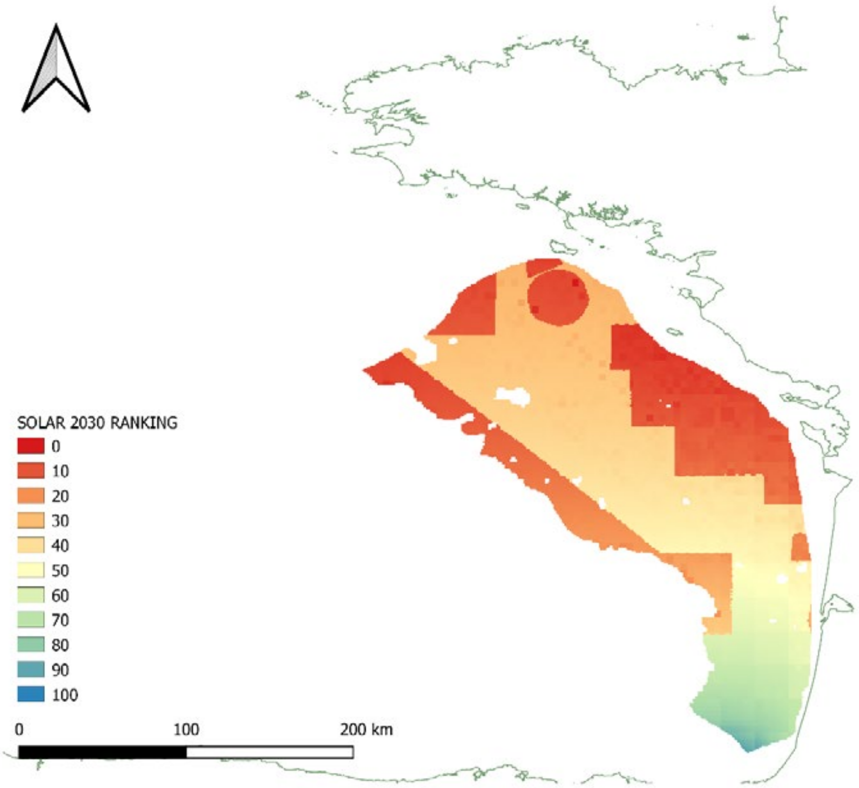

FIGURE 104 : FLOATING SOLAR PHOTOVOLTAICS RANKING INDEX FOR 2030 OFFSHORE FRANCE

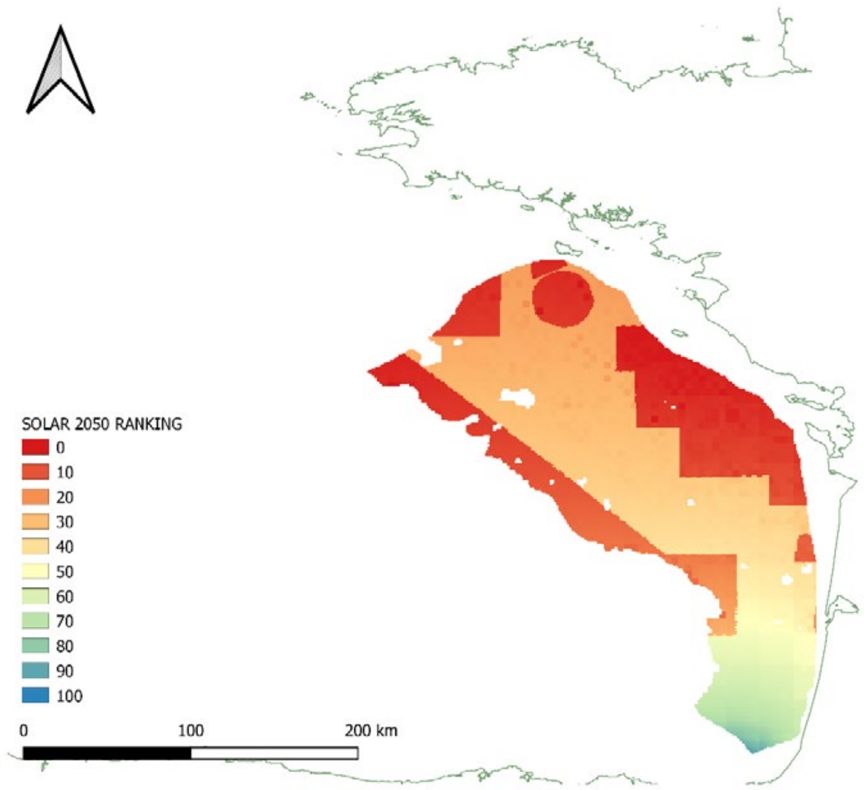

FIGURE 105 : FLOATING SOLAR PHOTOVOLTAICS RANKING INDEX FOR 2050 OFFSHORE FRANCE

The offshore Southern offshore part of France (Figure 104 and Figure 105) highlights a large area with high scores, over 90, in the Bay of Biscay. Advancing towards the North the scores reduce along with solar radiation.

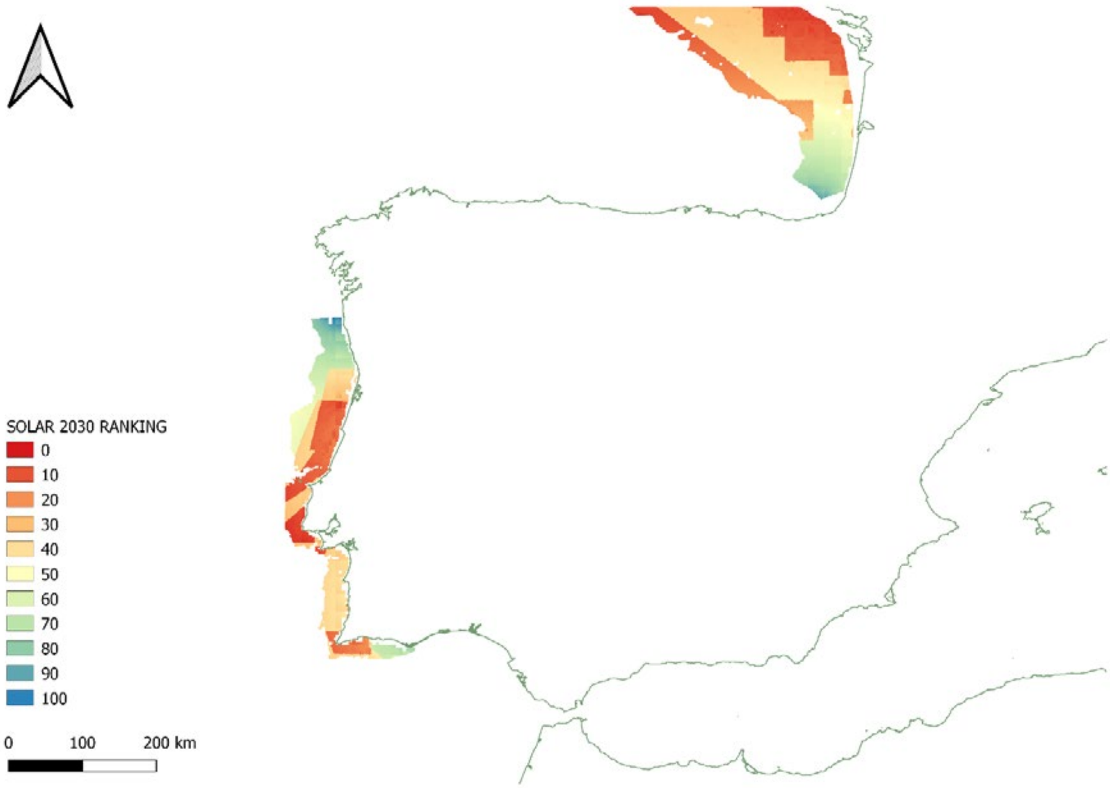

FIGURE 106 : FLOATING SOLAR PHOTOVOLTAICS RANKING INDEX FOR 2050 OFFSHORE THE IBERIAN PENINSULA

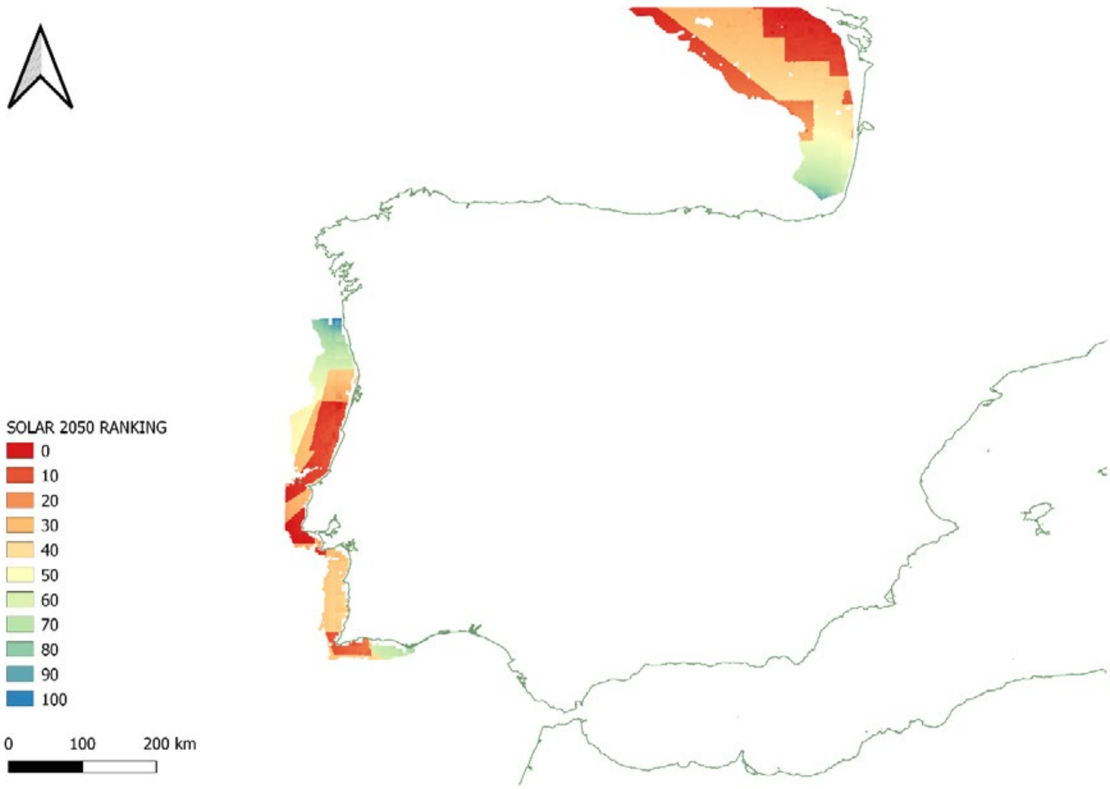

FIGURE 107 : FLOATING SOLAR PHOTOVOLTAICS RANKING INDEX FOR 2050 OFFSHORE THE IBERIAN PENINSULA

The Iberian Peninsula maps are presented in Figure 106 and Figure 107 for 2030 and 2050, respectively. The Southern regions of Portugal, near to the Gibraltar strait, are outside the military zones, and therefore they achieve high scores, similar to those North of Portugal. The difference between restricted and non-restricted areas becomes more pronounced in the 2050 scenario.

5.1.2.4 Tidal stream energy

Tidal stream zones are highly localised. Therefore, the figures are restricted to Ireland and France, where the majority of tidal resource is concentrated. Specific areas in the Iberian Peninsula may be consulted in the literature cited in previous chapters.

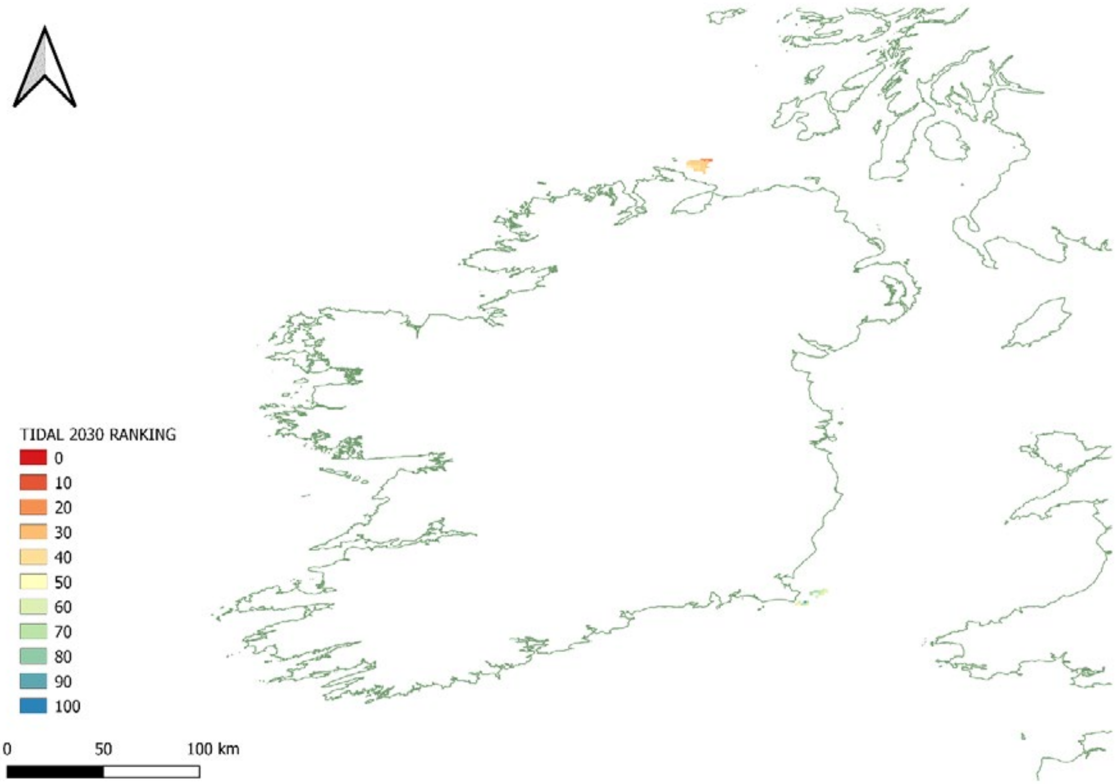

FIGURE 108 : TIDAL ENERGY RANKING INDEX FOR 2030 OFFSHORE IRELAND

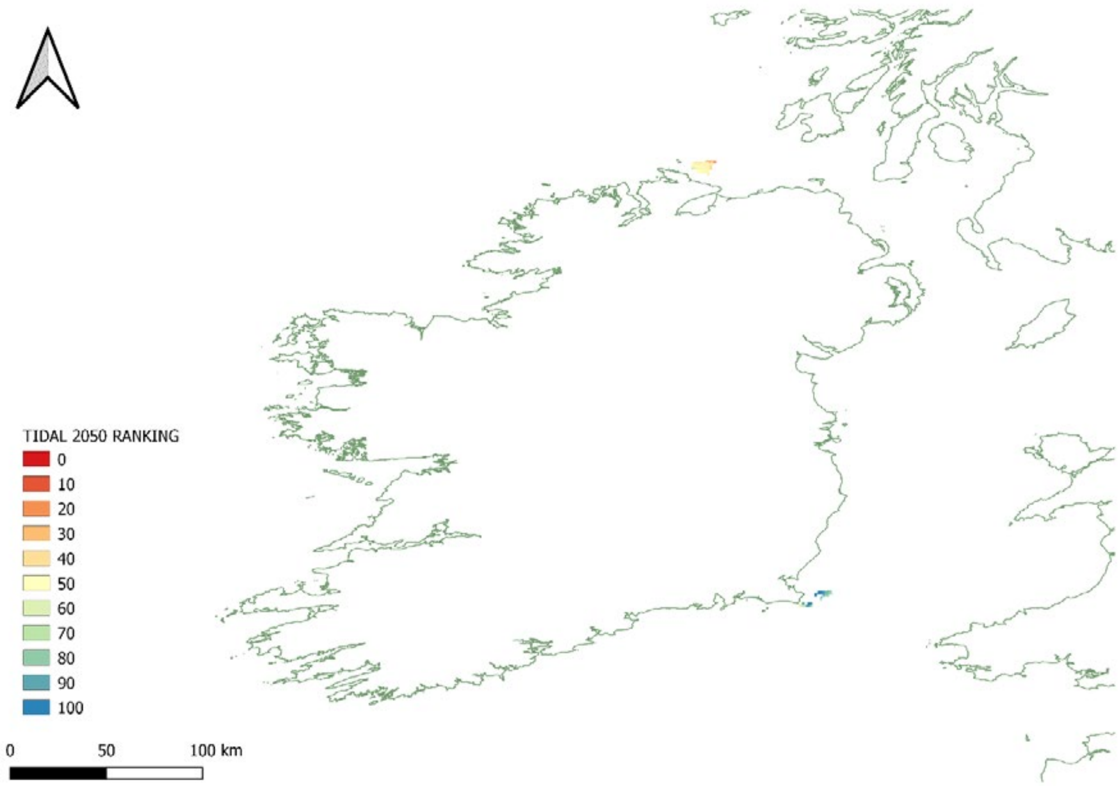

FIGURE 109 : WAVE ENERGY RANKING INDEX FOR 2050 OFFSHORE IRELAND

As regards the Irish region (Figure 108 and Figure 109 for 2030 and 2050, respectively), scores reach 40 to 50, with the exception of a small area in Southeastern Ireland.

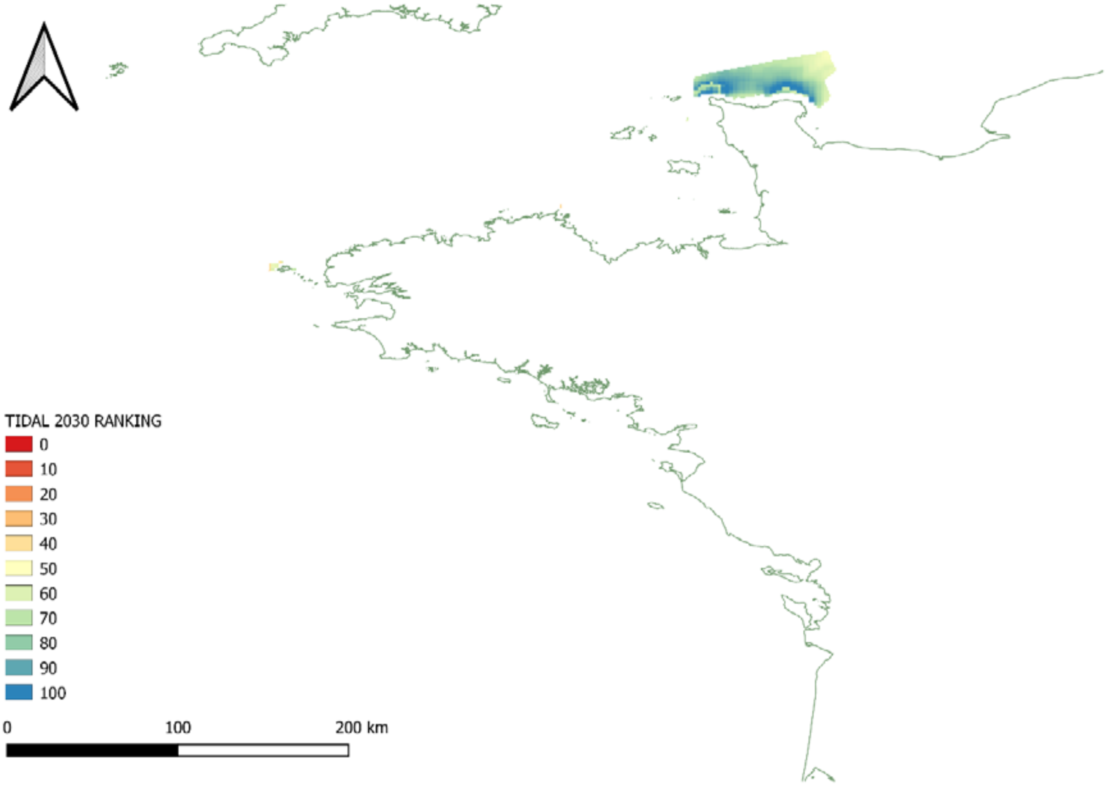

FIGURE 110 : TIDAL ENERGY RANKING INDEX FOR 2030 OFFSHORE FRANCE

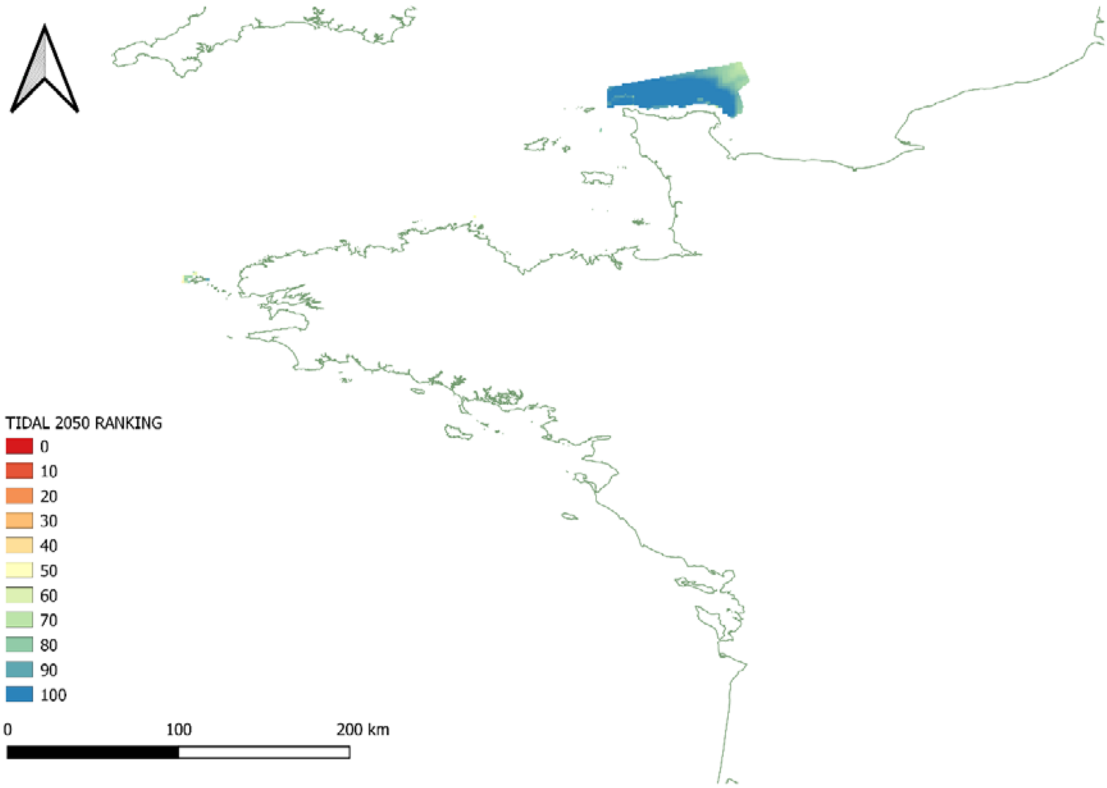

FIGURE 111 : TIDAL ENERGY RANKING INDEX FOR 2050 OFFSHORE FRANCE

The French region (Figure 110 and Figure 111) presents the highest scores for tidal stream energy. The main area, located off the Normandy coast, has scores close to 100 and a large surface area for tidal stream exploitation. This area is undoubtedly the most promising for this technology. Its score increases significantly in the 2050 scenario.

6. CONCLUSIONS

In this report the potential for offshore renewable energy in the European Atlantic has been investigated. More specifically, offshore wind, wave, tidal stream and solar PV have been considered, given that other forms of offshore renewable energy, e.g., OTEC, have very limited potential in the region.

Chapter 1 analyses the potential for offshore renewable energy generation based on the resources and the "state of play". Importantly, "hot spots", i.e., areas with great potential, are identified for the different technologies, and the technical challenges for their development are reviewed.
The Levelised Cost of Energy (LCOE) is bound to affect this development. It is arguably the single most important metric to consider, and therefore has been analysed *in extenso* in Chapter 2, with two time horizons, 2030 and 2050. Importantly, the assessment covers the four technologies considered and the entire European Atlantic.

Connecting future offshore facilities to the mainland grid is another important element in the development of offshore renewable energy. Chapter 3 analyzed in detail the options for these connections (radial, hybrid), considering their pros and cons and, last but not least, their cost. While radial options appear as less costly in general than the hybrid alternatives, hybrid projects bring additional advantages, for instance in terms of security of supply.

The challenges and barriers to the implementation of offshore renewable energy in the European Atlantic are covered in Chapter 4. Five categories of non-technical implementation challenges are addressed: regulatory and administrative, socio-ecological, economic and financial, MSP and multi-use, supply chain. This is complemented by the analysis of the national strategies to mitigate these challenges in the four countries considered in this study.

Finally, a quantitative method to rank the areas pre-selected in Chapter 1 is developed in Chapter 5. The method combines a number of criteria, which take into account the LCOE calculated in Chapter 2 and other uses of the marine space (military, nature reserves, fishing, shipping lanes, oil & gas, communication cables), where appropriate. The method has the advantage that it lends itself to a homogeneous application to different technologies, and it is indeed applied to the four considered in this study with two time horizons (2030 and 2050). The results are a quantitative classification of pre-selected areas on a 100-point scale and, thus, the identification of prime areas for the development of offshore renewable energy in the European Atlantic.

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APPENDICES

APPENDIX 1

A1.1 Detail of offshore wind energy projects

A1.1.1 Republic of Ireland

WIND (WI)						
Country	**Project name**	**Installed capacity**	**Consortium**	**Technology**	**Status**	**Expected delivery date or running time**
[redacted]						
Republic of Ireland	Arklow Bank Phase 1	25.2 MW	ACCIONA Energia, GE Energy, SSE Renewables.	Fixed	Operational	2003
Republic of Ireland	Arklow Bank Phase 2	520 MW	SSE Renewables	Fixed	Early Planning/Call for projects	2025
Republic of Ireland	Codling Bank	1100 MW	EDF Energies Nouvelles & Fred Olsen Renewables Ltd.	Fixed	Early Planning/Call for projects	2025
Republic of Ireland	Oriel	330 MW	Parkwind NV, ESB	Fixed	Awarded	not specified
Republic of Ireland	Dublin Array	900 MW	Saorgus Energy Ltd., RWE Renewables	Fixed	Early Planning/Call for projects	2027
Republic of Ireland	Sceirde Rocks	400 MW	Fuinneamh Sceirde Teoranta	Fixed	Early Planning/Call for projects	2030
Republic of Ireland	North Irish Sea Array	530 MW	Statkraft	Fixed	Early Planning/Call for projects	2026
Republic of Ireland	Moneypoint Offshore One	400 MW	ESB	Floating	Early Planning/Call for projects	2030
Republic of Ireland	Moneypoint Offshore Two	1100 MW	ESB	Floating	Early Planning/Call for projects	2030
Republic of Ireland	Ilen	1100 MW	Simply Blue Energy Ltd., Shell Wind Energy Ltd	Floating	Early Planning/Call for projects	not specified
Republic of Ireland	Clarus	1000 MW	DP Energy Ireland Ltd, Iberdrola Renovables Energia, S.A.	Floating	Early Planning/Call for projects	not specified
Republic of Ireland	Inis East 1	500 MW	Inis Offshore Wind	Fixed	Early Planning/Call for projects	2030
Republic of Ireland	Inis East 2	500 MW	Inis Offshore Wind	Fixed	Early Planning/Call for projects	2030
Republic of Ireland	Inis South	1000 MW	Inis Offshore Wind	Fixed and floating	Early Planning/Call for projects	2030
Republic of Ireland	Inis West 1	1000 MW	Inis Offshore Wind	Fixed and floating	Early Planning/Call for projects	2030

Republic of Ireland	Inis West 2	1000 MW	Inis Offshore Wind	Fixed and floating	Early Planning/Call for projects	2030
Republic of Ireland	ANIAR Offshore Array - phase 1	500 MW	Aniar Offshore ltd.	Fixed	Early Planning/Call for projects	not specified
Republic of Ireland	ANIAR Offshore Array - phase 2	500 MW	Aniar Offshore ltd.	Floating	Early Planning/Call for projects	not specified
Republic of Ireland	Urban Sea	4000 MW	Enterprize Energy PTE. LTD.	Floating	Early Planning/Call for projects	not specified
Republic of Ireland	Emerald	1000 MW	Simply Blue Energy Ltd., Shell New Energies	Floating	Early Planning/Call for projects	not specified
Republic of Ireland	Inis Ealga Marine Energy Park	1000 MW	DP Energy Ireland Ltd,Iberdrola Renovables Energia, S.A.	Floating	Early Planning/Call for projects	2030
Republic of Ireland	North Celtic Sea	600-800 MW	Energia Renewables	Fixed	Early Planning/Call for projects	2030
Republic of Ireland	SSE Renewables Celtic Sea	800 MW	SSE Renewables	Floating	Early Planning/Call for projects	2030
Republic of Ireland	Shelmalere	1000 MW	DP Energy Ireland Ltd, Iberdrola Renovables Energia, S.A.	Fixed	Early Planning/Call for projects	not specified
Republic of Ireland	Kilmichael Point	500 MW	ESB	Fixed	Early Planning/Call for projects	not specified
Republic of Ireland	South Irish Sea	600-1330 MW	Energia Renewables	Fixed	Early Planning/Call for projects	not specified
Republic of Ireland	Latitude 52	1000 MW	DP Energy Ireland Ltd	Fixed	Early Planning/Call for projects	not specified
Republic of Ireland	Cailleach	1600 MW	Ocean Winds	Fixed	Early Planning/Call for projects	not specified
Republic of Ireland	Greystones	1000 MW	COBRA INSTALACIONES Y SERVICIOS, S.A., Flotation Energy plc	Fixed	Early Planning/Call for projects	2027
Republic of Ireland	Clogher Head	500 MW	ESB, Parkwind NV	Fixed	Early Planning/Call for projects	not specified
Republic of Ireland	Cooley Point	500 MW	Hibernian Wind Power Ltd	Fixed	Early Planning/Call for projects	2027
Republic of Ireland	SSE Renewables Braymore Point	800 MW	SSE Renewables	Fixed	Early Planning/Call for projects	not specified
Republic of Ireland	Blackwater	1500 MW	COBRA INSTALACIONES Y SERVICIOS, S.A.,Flotation Energy plc	Floating	Early Planning/Call for projects	not specified

Name	Country	Technology	Type of project	Status
Arklow Bank Phase 1	**Republic of Ireland**	**Bottom-fixed**	**Pilot**	**Operational**

Phase 1 of the Arklow Bank wind farm was constructed in 2003/04 consisting of seven wind turbines with a capacity of 25.2 MW. Arklow Bank Phase 1 is owned and operated by GE Energy under a sublease to the foreshore lease and remains the first and only operational offshore wind farm in Ireland.

Arklow Bank Phase 1 (Source: SSE Renewables

- It is located on the Arklow Bank, a shallow water sandbank in the Irish Sea, around 10 kilometers off the coast of Arklow with an area of 27 by 2.5 km.
- Seven 3.6 MW generators spaced 600 m apart (steel monopile foundations).
- Phase 2 of Arklow Bank Wind Park will be located on and around the Arklow Bank, approximately 6 to 13 km from the shore, and will increase the capacity up to 520 MW.

More information: https://www.sserenewables.com/offshore-wind/projects/arklow-bank-wind-park/

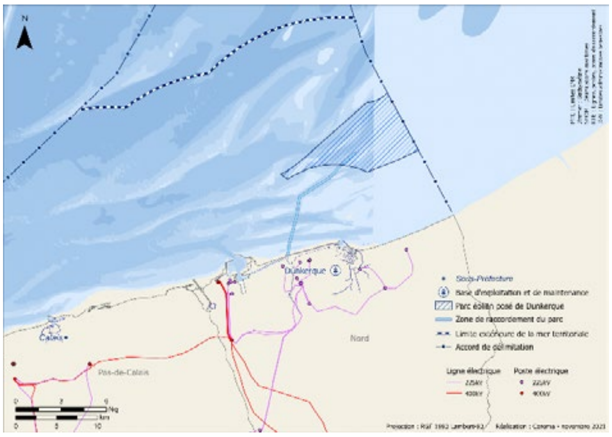
A1.1.2 France

WIND (WI)						
Country	**Project name**	**Installed capacity**	**Consortium**	**Technology**	**Status**	**Expected delivery date or running time**
France	Floatgen	2 MW	Demonstration	Floating	Operational	2018
France	Dunkerque	600 MW	EDF Renouvelables Innogy, Blauracke	Fixed, monopile	Consent authorized	2026
France	Dieppe Le Tréport	496 MW	Engie EDP renewables Sumitomo Caisse des Dépôts	Fixed, jacket	Under construction	2024
France	Fécamp	497 MW	EDF Energies Nouvelles, Enbridge WPD Offshore	Fixed, gravity base	Under construction	2023
France	Courseulles-sur Mer	448 MW	EDF Energies Nouvelles Enbridge WPD Offshore	Fixed, monopile	Under construction	2024
France	Ailes marines	496 MW	IBERDROLA	Fixed, jacket	Under construction	2023
France	Parc éolien en mer de St Nazaire	480 MW	EDF Renouvelables Enbridge	Fixed, monopile	operational	2022
France	Eoliennes en mer des iles Yeu Noirmoutiers	496 MW	Engie EDP renewables Sumitomo Caisse des Dépôts	Fixed, jacket	Under construction	2024
France	Normandie 1 GW	1 GW	Awarded in 2023	Not specified	Early Planning/Call for projects	2028-2029
France	Bretagne sud offshore wind farm	250 MW	Awarded in 2022	Floating	Early Planning/Call for projects	Not specified
France	Oléron fixed offshore wind farm	500 to 1000 MW	not specified	Fixed	Early Planning/Call for projects	Not specified

Name	Country	Technology	Type of project	Status
Parc éolien en mer de Dunkerque	**France**	**Fixed monopile wind turbine**	**Commercial**	**Consented**

The project comes from the 3rd call for tenders targeting offshore wind energy in France and launched by the government in 2016. The construction of the 600 MW farm should start in 2024 and the operation in 2027

- Consortium is represented by EDF Renouvelables, Innogy SE, Blauracke GmbH (Enbridge) and was awarded in 2019
- Turbines: 46
- Distance to shore: 10 km
- Surface: 50 km²
- Harbor for operation and maintenance: Dunkerque
- Expected production equivalent to the electricity consumption of 1 000 000 people



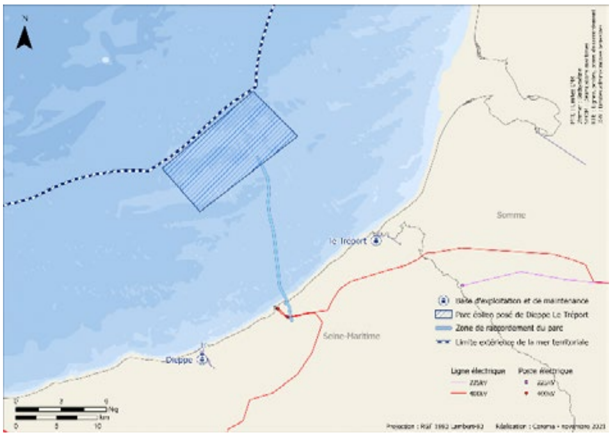
POSITION OF THE PARC EOLIEN DE DUNKERQUE CONSENTED SITE

More information: https://parc-eolien-en-mer-de-dunkerque.fr/

Name	Country	Technology	Type of project	Status
Parc éolien en mer de Dieppe Le Tréport	**France**	**Fixed jackets wind turbine**	**Commercial**	**Under construction**

The project comes from the 2nd call for tenders targeting offshore wind energy in France and launched by the government in 2013. The construction of the 496 MW farm has started in 2021 and the operation should start in 2024

- Consortium is represented by Engie, EDP Renewables, Sumitomo, Groupe la Caisse des Dépôts and was awarded in 2014
- Turbines (Siemens-Gamesa D8 model): 62 x 8 MW
- Distance to shore: 15.5 km
- Surface: 83 km²
- Harbor for operation and maintenance: Dieppe
- Expected production equivalent to the electricity consumption of 630 000 people



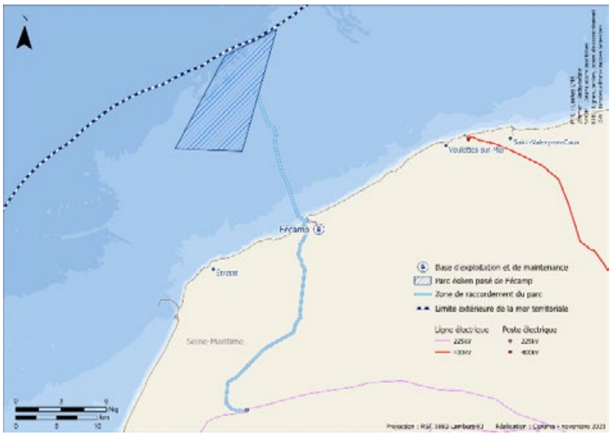
POSITION OF THE PARC ÉOLIEN DE DIEPPE LE TRÉPORT CONSENTED SITE

More information: https://dieppe-le-treport.eoliennes-mer.fr/

Name	Country	Technology	Type of project	Status
Parc éolien en mer de Fécamp	**France**	**Fixed gravity base wind turbine**	**Commercial**	**Under construction**

The project comes from the 1rst call for tenders targeting offshore wind energy in France and launched by the government in 2011. The construction of the 497 MW farm has started in 2020 and the operation should start in 2023

- Consortium is represented by EDF Energies Nouvelles, Enbridge and WPD Offshore and was awarded in 2012
- Turbines: 71 x 7 MW
- Distance to shore: 12 km
- Surface: 60 km²
- Harbor for operation and maintenance: Fécamp
- Expected production equivalent to the electricity consumption of 777 000 people



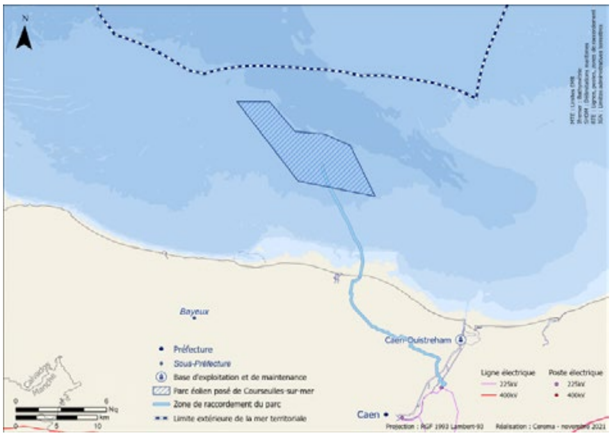
Position of the Parc éolien de Fécamp consented site

More information: https://parc-eolien-en-mer-de-fecamp.fr/

Name	Country	Technology	Type of project	Status
Parc éolien en mer du Calvados	**France**	**Fixed monopile wind turbine**	**Commercial**	**Under construction**

The project comes from the 1rst call for tenders targeting offshore wind energy in France and launched by the government in 2011. The construction of the 448 MW farm has started in 2021 and the operation should start in 2024

- Consortium is represented by EDF Energies Nouvelles, Enbridge and WPD Offshore and was awarded in 2012
- Turbines (Siemens-Gamesa): 64 x 7 MW
- Distance to shore: 10 km
- Surface: 50 km²
- Harbor for operation and maintenance: Caen-Ouistreham
- Expected production equivalent to the electricity consumption of 630 000 people



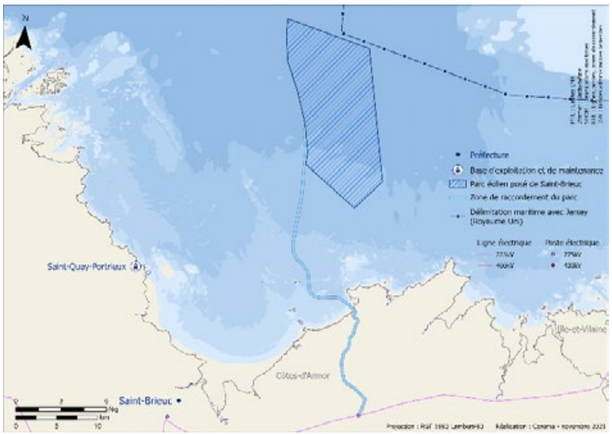
Position of the Parc éolien de du Calvados consented site

More information: https://www.parc-eolien-en-mer-du-calvados.fr/

Name	Country	Technology	Type of project	Status
Ailes Marines (Iberdrola)	**France**	**Fixed jackets wind turbine**	**Commercial**	**Under construction**

The project comes from the first call for tenders targeting offshore wind energy in France and launched by the government in 2011. The commissioning of the 496 MW wind farm is expected to start in 2023.

- Consortium is represented by Iberdrola and was awarded in 2012
- Turbines (Siemens-Gamesa D8 model): 62 x 8 MW
- Closest point to shore 16.3 km
- Surface: 75 km²
- Harbor for operation and maintenance: Saint-Quay-Portrieux
- Expected production equivalent to the electricity consumption of 835 000 people



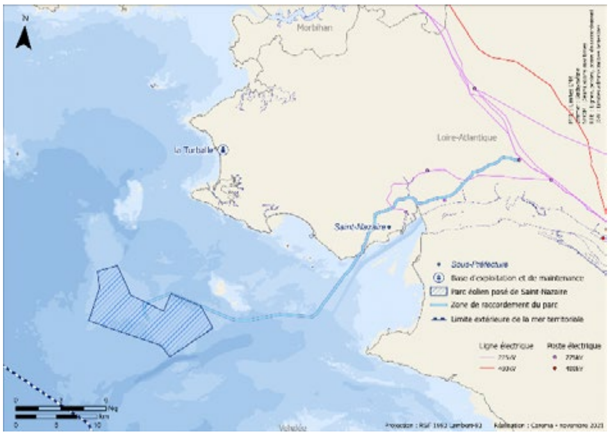
POSITION OF THE PARC ÉOLIEN AILES MARINES CONSENTED SITE

More information: https://ailes-marines.bzh/le-projet/

Name	Country	Technology	Type of project	Status
Parc éolien en mer du banc de Guérande	**France**	**Fixed monopile wind turbine**	**Commercial**	**Operating**

The project comes from the 1rst call for tenders targeting offshore wind energy in France and launched by the government in 2011. The construction of the 480 MW farm has started in 2020 and the operation should start in 2022

- Consortium is represented by EDF Energies Nouvelles and Enbridge, and was awarded in 2012
- Turbines (General Electrics - Heliade 150 model): 80 x 6 MW
- Distance to shore: 12 km
- Surface: 78 km²
- Harbor for operation and maintenance: La Turballe
- Expected production equivalent to the electricity consumption of 720 000 people



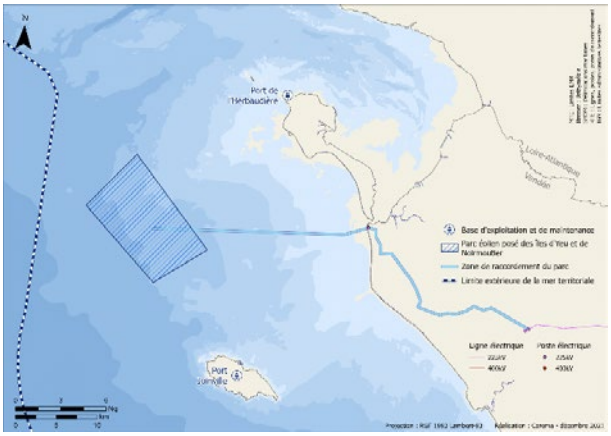
POSITION OF THE PARC ÉOLIEN DU BANC DE GUÉRANDE CONSENTED SITE

More information: https://parc-eolien-en-mer-de-saint-nazaire.fr/

Name	Country	Technology	Type of project	Status
Parc éolien en mer des deux îles	**France**	**Fixed monopile wind turbine**	**Commercial**	**Under construction**

The project comes from the 2nd call for tenders targeting offshore wind energy in France and launched by the government in 2013. The construction of the 496 MW farm has started in 2021 and the operation should start in 2024

- Consortium is represented by Engie, EDF Renewables, Sumitomo and Groupe Caisse des Dépôts, and was awarded in 2014
- Turbines (Siemens-Gamesa D8 model): 62 x 8 MW
- Distance to shore: 12 km
- Surface: 83 km²
- Harbor for operation and maintenance: Port-Joinville and l'Herbaudière
- Expected production equivalent to the electricity consumption of 800 000 people



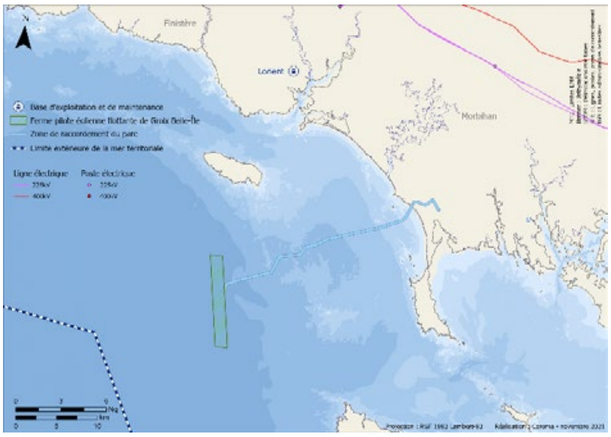
POSITION OF THE PARC ÉOLIEN DES DEUX ILES CONSENTED SITE

More information: https://iles-yeu-noirmoutier.eoliennes-mer.fr/

Name	Country	Technology	Type of project	Status
				CANCELLED

The project comes from the call for tenders targeting floating offshore wind energy in France and launched by ADEME in 2015. The construction of the 28.5 MW pilot farm has started in 2021 and the operation should start in 2022 or 2023.

- Consortium is represented by EOLFI, Méridiam RCF and Groupe Caisse des Dépôts, and was awarded in 2016
- Turbines (MHI Vestas): 3 x 9.5 MW
- Distance to shore: 22 km
- Surface: 14 km²
- Harbor for operation and maintenance: Lorient
- Expected production equivalent to the electricity consumption of 47 000 people



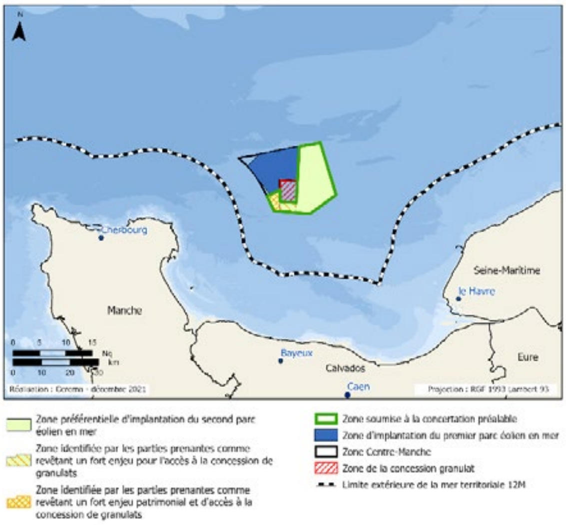
POSITION OF THE EOLIENNES FLOTTANTES DE GROIX ET BELLE-ILE CONSENTED SITE

More information: https://eoliennes-groix-belle-ile.com/

Name	Country	Technology	Type of project	Status
Projets Centre Manche 1 and 2	France	Not specified	Commercial	Planned

The French government has launched a call for tenders for a 1 GW commercial wind farm offshore Normandy according to the ongoing NECP.

- A 500 km² site was identified following public consultation in 2020
- The competitive bidding process was launched in January 2021
- The competitive dialog was launched in April 2021 for the 6 short-listed candidates
- The deadline for the submission of the tenders is set to summer 2022 for a final decision forseen before the end of 2022
- The construction of a second farm should be decided in 2023 (Projet Centre Manche 2) after a competitive bidding process is launched



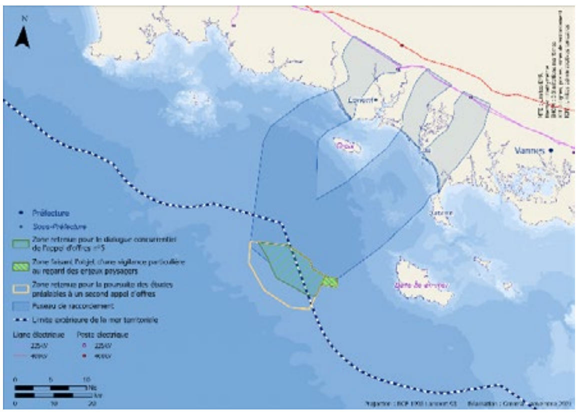
Position of the Projects Centre Manche 1 and 2 consented sites

More information: https://www.eoliennesenmer.fr/facades-maritimes-en-france/facade-manche-mer-du-nord/projet-centre-manche and https://www.eoliennesenmer.fr/facades-maritimes-en-france/facade-manche-mer-du-nord/projet-centre-manche-2

Name	Country	Technology	Type of project	Status
Projet en Bretagne Sud	France	Not specified	Commercial	Planned

The French government has launched a call for tenders for a 250 MW commercial floating wind farm offshore South of Brittany according to the ongoing NECP.

- The public consultation lasted from July to December 2020
- The competitive bidding process was launched in April 2021
- 10 candidates were short-listed in September 2021
- The competitive dialog will end in spring 2022
- The project should be awarded in early 2023



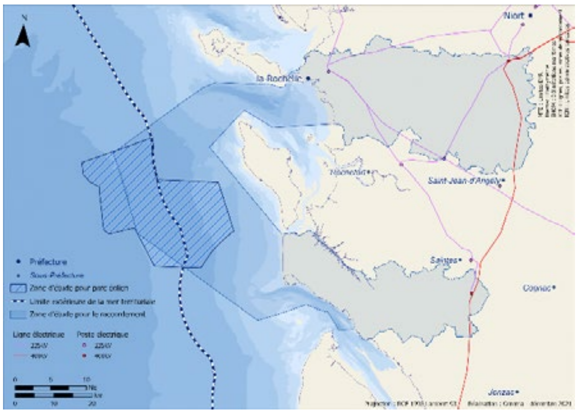
Position of the Projet en Bretagne Sud consented site

Moreinformation: https://www.eoliennesenmer.fr/facades-maritimes-en-france/facade-nord-atlantique-manche-ouest/projet-en-bretagne-sud

Name	Country	Technology	Type of project	Status
Projet en Bretagne Sud	**France**	**Not specified**	**Commercial**	**Planned**

The French government has launched a call for tenders for a 500 to 1000 MW fixed offshore wind farm offshore Oléron Island according to the ongoing NECP.

- The public consultation about the consenting area started in September 2021 and will last until February 2022
- The competitive bidding process was launched in April 2021
- 10 candidates were short-listed in September 2021
- The competitive dialog will end in spring 2022
- The project should be awarded in early 2023



Position of the Projet Sud Atlantique study area for which public consultation is ongoing

More information: https://www.eoliennesenmer.fr/facades-maritimes-en-france/facade-sud-atlantique/projet-en-sud-atlantique

A.1.3 Spain

WIND (WI)						
Country	**Project name**	**Installed capacity**	**Consortium**	**Technology**	**Status**	**Expected delivery date or running time**
[redacted]						
Spain	DemoSATH	2 MW	Saitec Offshore Technology	Floating	Under construction	2022
Spain	Not specified	MW-scale	Marine Power System	Floating Wind + Waves	Pilot/Demonstration	2023

DEPLOYMENT OF THE ELISA PROTOTYPE OF GRAVITY-BASED SUPPORT STRUCTURE (ESTEYCO) AT PLOCAN, GRAN CANARIA (SOURCE: ESTEYCO)

A1.1.4 Portugal

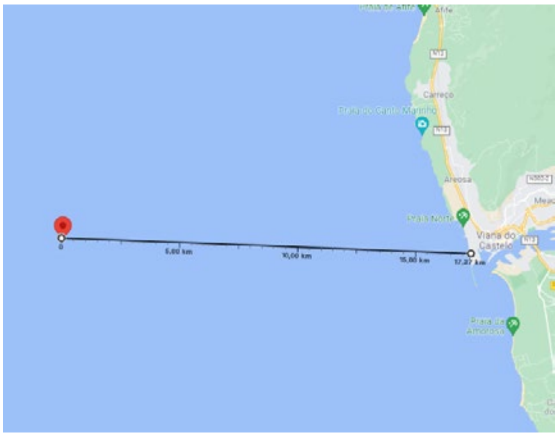
WIND (WI)						
Country	**Project name**	**Installed capacity**	**Consortium**	**Technology**	**Status**	**Expected delivery date or running time**
Portugal	Windfloat Atlantic	25 MW	Ocean Winds; Repsol and Principle Power Inc.	Floating	Operational	2020

Name	Country	Technology	Type of project	Status
WindFloat Atlantic	**Portugal**	**Semi-submersible, catenary mooring**	**Semi-Commercial**	**In operation**

The WindFloat Project has developed an innovative technology to allow the exploration of wind potential at sea, at depths of over 40m. The first platform was connected in 2019 and the final and third platform in May 2020, from when the farm became fully operational.

- Owned by a joint venture of Ocean Winds, Principle Power and Repsol.
- Turbines: 3
- Capacity per turbine 8.4 MW
- Distance to shore: 18 km
- Surface: 17 km²
- Sea depth range: 100m
- Harbor for O&M: Viana do Castelo
- Expected production equivalent to the electricity consumption of 60 000 families.
- Implantation area coordinates:

ID	Latitude	Longitude
A	41º41'50.992" N	9º05'15.356"W
B	41º41'52.564"N	9º02'00.770"W
C	41º40'31.543"N	9º01'59.639"W
D	41º40'29.972"N	9º05'14.157"W



POSITION OF THE WINDFLOAT ATLANTIC

More information: https://www.oceanwinds.com/projects/windfloat-atlantic-project/

A1.2 Detail of wave energy projects

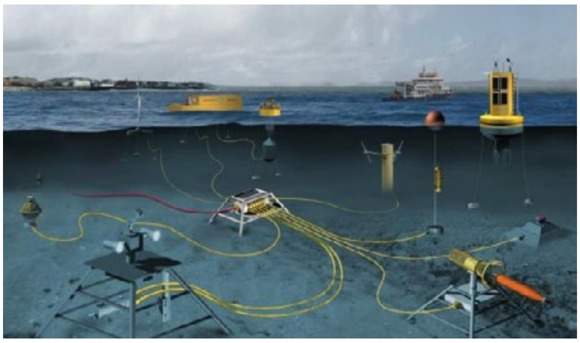
A1.2.1 Republic of Ireland

WAVE (WA)						
Country	**Project name**	**Installed capacity**	**Consortium**	**Technology**	**Status**	**Starting/Delivery date or running time**
Republic of Ireland	WestWave	5 MW	ESB	Not specified	Pilot/Demonstration	Not specified
Republic of Ireland	Saoirse	5 MW	Simply Blue Energy Ltd.	Surface point absorber	Pilot/Demonstration	2026
Republic of Ireland	Ocean Energy Buoy (Galway Bay Test Site)	N/A	Irish Marine Institute, Sustainable Energy Authority of Ireland (SEAI), AWS Ocean Energy, Aalborg University	Oscillating water column	Decomissionned	2006
Republic of Ireland	AMETS (test site)	N/A	Sustainable Energy Authority of Ireland	Not specified	Pilot/Demonstration	Not specified

Name	Country	Technology	Type of project	Status
Galway Bay Test Site	**Republic of Ireland**	**Wave**	**Test site**	**Operational**

The Galway Bay ¼ scale Wave Energy Test Site is located 1.5 km offshore in water depths ranging from 20-23 m. The license for the site has been held by the Marine Institute since 2006. The research infrastructure on the site has recently been upgraded with the Galway Bay Sub Sea Cable Observatory, providing a cabled national test and demonstration facility for marine energy and technology. In total, it consists of 3 components:

- A standard telecommunications cable from a shore station to the wave energy test site providing power and data connectivity
- Subsea test and monitoring platforms
- Floating sea station platform



Impression of the Galway Bay test site. Photograph: SmartBay

More information: https://www.marine.ie/Home/site-area/infrastructure-facilities/ocean-energy/galway-bay-test-site-0

A1.2.2 France

WAVE (WA)						
Country	**Project name**	**Installed capacity**	**Consortium**	**Technology**	**Status**	**Starting/Delivery date or running time**
France	Wavegem	150 kW	Geps Techno	Point absorber	Pilot/Demonstration	2019-2021

A1.2.3 Spain

WAVE (WA)						
Country	**Project name**	**Installed capacity**	**Consortium**	**Technology**	**Status**	**Starting/Delivery date or running time**
Spain	Mitruku	300 kW	Demonstration	Oscillating water column	Operational	2011
Spain	Not specified	600 kW	Wello Saipem	Point absorber	Operational	2021
Spain	Not specified	MW-scale	Marine Power System	Floating Wind + Waves	Pilot/Demonstration	2023

THE MUTRIKU WAVE POWER PLANT (PHOTO: EVE)

A1.2.4 Portugal

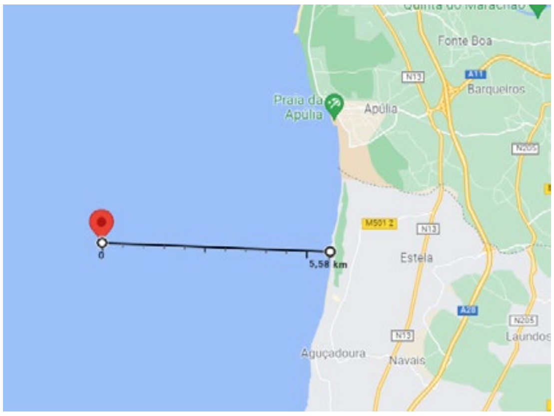
WAVE (WA)						
Country	**Project name**	**Installed capacity**	**Consortium**	**Technology**	**Status**	**Starting/Delivery date or running time**
[redacted]		[redacted]		[redacted]		
Portugal	HiWave-5	4 x 300 kW	CorPower	WEC	Under construction	2023
Portugal	WaveRoller	300 kW	AW-Energy	Oscillating Wave Surge Converter	Decomissionned	2019-2021 Decomissioned

Name	Country	Technology	Type of project	Status
HiWave-5	**Portugal**	**Point absorber WEC**	**Pre-Commercial**	**Under construction**

The project's will see CorPower's first commercial-scale C4 Wave Energy Converter deployed off the coast of Aguçadoura in 2022. This will later form part of a larger four-system WEC to be added until the end of 2023.

- Project developed by CorPower
- WEC's: 4
- WEC's capacity: 300 kW
- Distance to shore: 5.5 km
- Surface: 19.3 km²
- Sea depth: 50m
- Harbor for O&M: Póvoa do Varzim
- Implantation area coordinates:

ID	Latitude	Longitude
1	41°27'46.2''	8°50'32.4''
2	41°27'37.8''	8°50'6.6''
3	41°27'12.0''	8°50'21.0''
4	41°27'18.6''	8°50'46.2''



POSITION HIWAVE-5 INSTALLATION

More information: https://www.corpowerocean.com/projects/hiwave-5/

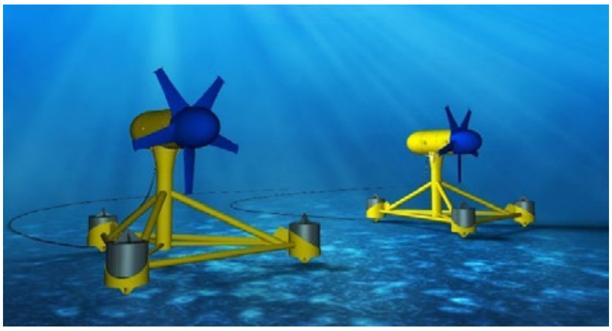
A1.3 Detail of tidal energy projects

A1.3.1 France

TIDAL (TI)						
Country	**Project name**	**Installed capacity**	**Consortium**	**Technology**	**Status**	**Expected delivery date or running time**
[redacted]						
France	FloWatt	7 x 2,5 MW	Hydroquest Qair	Vertical axis	Pilot/Demonstration	2025
France	Normandie Hydrolienne	4 x 3 MW	SIMEC Atlantis Development Agency for Normandie	Horizontal axis	Awarded	not specified
France	TIGER - Minesto	100 kw	Minesto	Kite	Pilot/Demonstration	2022
France	PHARES, Phase 1	2 x 500 kW	Akuo Energy Sabella	Horizontal axis	Pilot/Demonstration	2022
France	TIGER	2 x 250 kW	Sabella	Horizontal axis	Awarded	2025

Name	Country	Technology	Type of project	Status
PHARES Phase 1	**France**	**Bottom fixed tidal turbine**	**Pilot**	**Planned**

Part of the PHARES project to provide Ushant island with electricity (800 inhabitants). Multi-energy setup combining tidal turbines (SABELLA 2 x 500 kW), wind turbine (0.9 MW), solar (480 kW) and storage. The consortium is led by AKUO Energy with fundings coming from Région Bretagne and Programme Investissement d'Avenir.



SOURCE: SABELLA

- Up to 65% of renewable energy contribution to the electrical production of Ushant island
- Contributes to the decarbonization of Ushant island electricity production (2000 m^3 of fuel/yr)
- Challenging multi-energy project

More information: https://www.sabella.bzh/fr/les-projets/phares

Name	Country	Technology	Type of project	Status
TIGER	**France**	**Various tidal technologies**	**Pilot**	**Planned**

Part of the Tidal Stream Industry Energiser project (TIGER) funded by Interreg France (Channel) England Programme. The project was launched in 2019 and will be completed in 2023 with principal mission to energize and trigger the growth of the tidal energy sector.

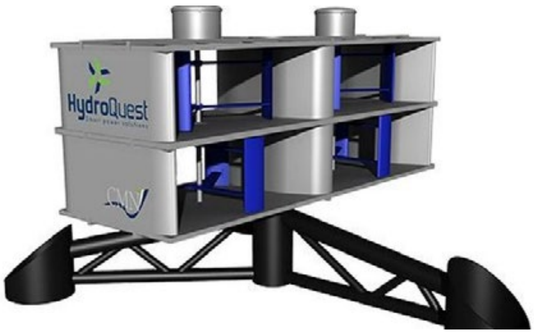
TIGER
TIDAL STREAM INDUSTRY ENERGISER

- Test of kite technology at Paimpol-Bréhat test site (Minesto, 100 kW)
- Consenting procedures launched for 2 additional tidal energy sites in Raz Blanchard and 1 in Gulf of Morbihan (SABELLA, 2 x 250 kW)
- Potential for tidal energy costs reduction down to 150€/MWh

More information https://interregtiger.com/, https://www.sabella.bzh/fr/les-projets/tiger

Name	Country	Technology	Type of project	Status
FloWatt	**France**	**Bottom fixed – vertical axis tidal turbines**	**Pilot**	**Planned**

The FloWatt project is a partnership between Qair and HydrQuest aiming at deploying a pilot farm composed of 7 x 2.5 MW vertical axis tidal turbines in the Raz Blanchard. This pilot farm will be the most powerful in the world and is expected to be a key element to strengthen the tidal energy industry.



- Construction planned for 2023 and operation for 2025
- 40 GWh/year – equivalent to the consumption of 20 000 people
- LCOE estimated to be 200 to 300 €/MWh

More information: https://www.hydroquest.fr/fermes-pilotes-hydroliennes/

APPENDIX 2

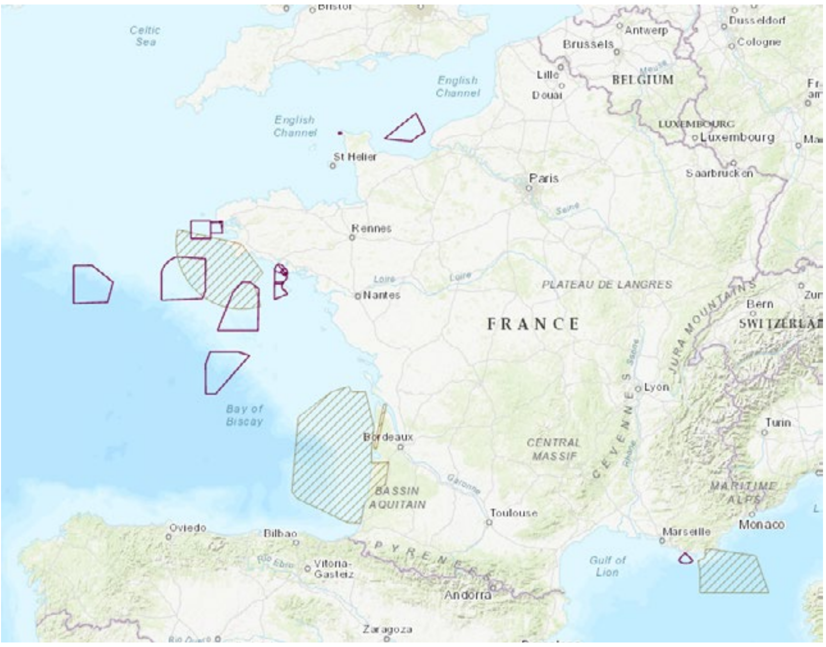
A2. Details of non-technical constraint layers

Features	Description	Source	Additional details
Marine Protected Areas (MPA)	**CDDA** The Common Databas on Designated Areas (CDDA) is the official source of marine protected areas for European countries. It inbcludes nationally designated areas such as marine conservation zones (MCZ), marine nature parks, nature reserves, national parks and other protected sites. **Natura2000** is an ecological network of protected areas setup to ensure the survival of Europe's most valuable species and habitats. It is based upon the 1979 Birds Directive and 1992 Habitats Directive. The database consists of special protection areas and sepcial conservation interests.	**CDDA:** EMODnet Human Activities, Environment, Nationally designated areas (CDDA) **Natura2000:** EMODnet Human Activities, Environment, Natura 2000	The Common Database on Designated Areas (CDDA) was created in 2014 by Cogea for the European Marine Observation and Data Network. It is entirely based on GIS Data from the European Environmental Agency's (EEA), plus external links and selected EEA tabular data joined by Cogea to the feature attributes, as well as a calculation by Cogea of marine and coastal location of features.The CDDA is commonly known as 'Nationally designated areas'. The data for the nationally designated protected areas inventory (CDDA) is delivered by the Eionet partnership countries. The CDDA is now an agreed annual Eionet core data flow maintained by the European Environment Agency (EEA) with support from the European Topic Centre on Biological Diversity (ETC/BD). The dataset is used by the EEA and e.g. the UNEP-WCMC for their main European and global assessments, products and services. The CDDA is the official source of protected area information from the 38 European countries to the World Database of Protected Areas (WDPA). The dataset on Natura 2000 sites was created in 2014 by Cogea for the European Marine Observation and Data Network. It is entirely based on spatial data from the European Environmental Agency (EEA), plus additional info, links and selected EEA data joined to the feature attributes, as well as a calculation by Cogea of marine and coastal location of features. Natura 2000 is an ecological network composed of sites designated under the Birds Directive (Special Protection Areas, SPAs) and the Habitats Directive (Sites of Community Importance, SCIs, and Special Areas of Conservation, SACs). The dataset covers the whole EU.
Oil and Gas	Hydrocarbon active extraction license	EMODnet Human Activities, Oil and Gas, Active Licences	The dataset on offshore active licences for Oil and Gas exploitation and exploration in the EU was created in 2014 by Cogea for the European Marine Observation and Data Network (EMODnet). It is the result of the aggregation and harmonization of datasets provided by several EU and non-EU sources. It is updated every year.

Cables	Telecommunication and power cable routes	EMODnet Human Activities, Telecommunication and power cables, Actual Routes	The datasets on subsea telecommunication and power cables (actual routes) in the EU was created in 2014 by Cogea for the European Marine Observation and Data Network (EMODnet). It is the result of the aggregation and harmonization of datasets provided by several sources. It is updated every year. The datasets contain lines representing actual cable routes locations.
Main Shipping Routes	Based on the main International Maritime Organization (IMO) shipping routes	EMODnet Human Activities: EMSA Route Density Map	The Route Density Maps are produced and provided to EMODnet by the European Maritime Safety Agency (EMSA).
Main Fishing Areas	The datasets on fishing intensity in the EU waters were created in 2021 by the International Council for the Exploration of the Sea (ICES). Fisheries overview data concern: i) the spatial distribution of average annual fishing effort (mW fishing hours) by ecoregion.	EMODnet Human Activities, Fisheries, Fishing intensity	Data provided by the International Council for the Exploration of the Sea (ICES)

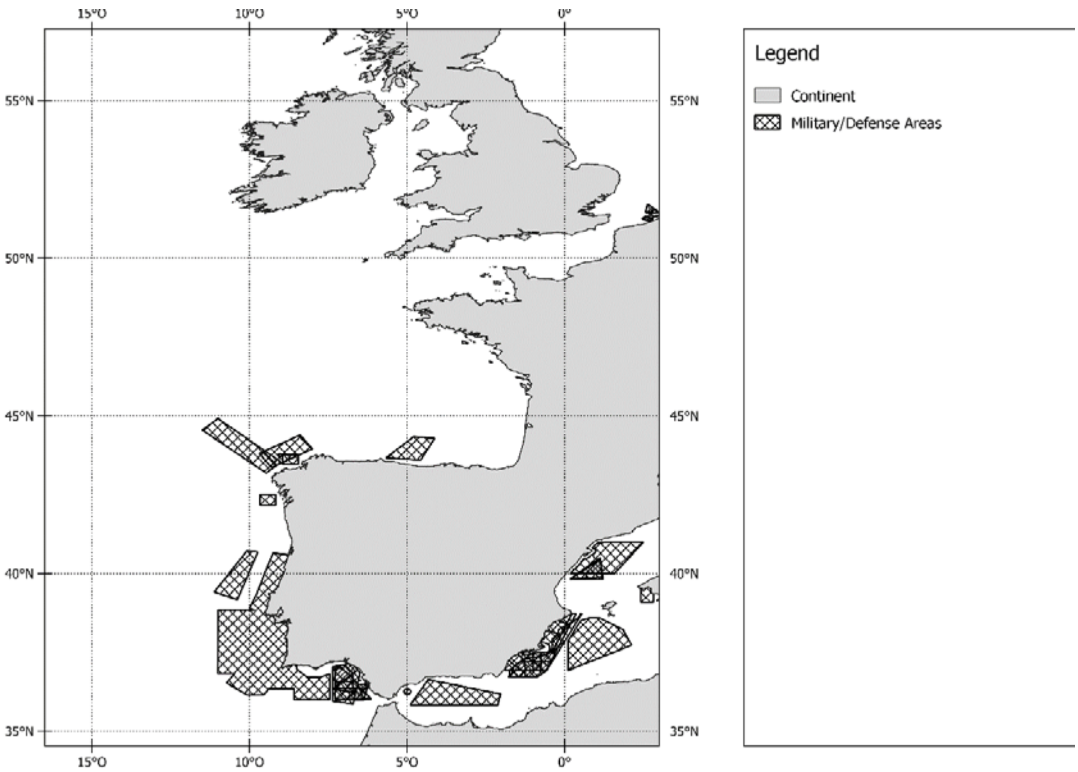
APPENDIX 3

A3. Selection of Military/Defense areas for France, Spain and Portugal



Firing areas for the Navy and the Air Forces in France, extracted from [74].

[74] https://experience.arcgis.com/experience/56a42302d55f431ba16d576be99e0424/



Military areas in Spain and Portugal from EMODNet database. The database on offshore military areas in the EU was created in 2020 by CETMAR for the European Marine Observation and Data Network (EMODnet). It is the result of the aggregation and harmonization of datasets provided by several sources and covers the Firing Area, Air Force Exercise, Surface Exercise, Underwater Exercise, Mine Hunting Exercise, National Defence Area for Spain and Portugal.

APPENDIX 4

A4.1 2030 Production scenarios per country

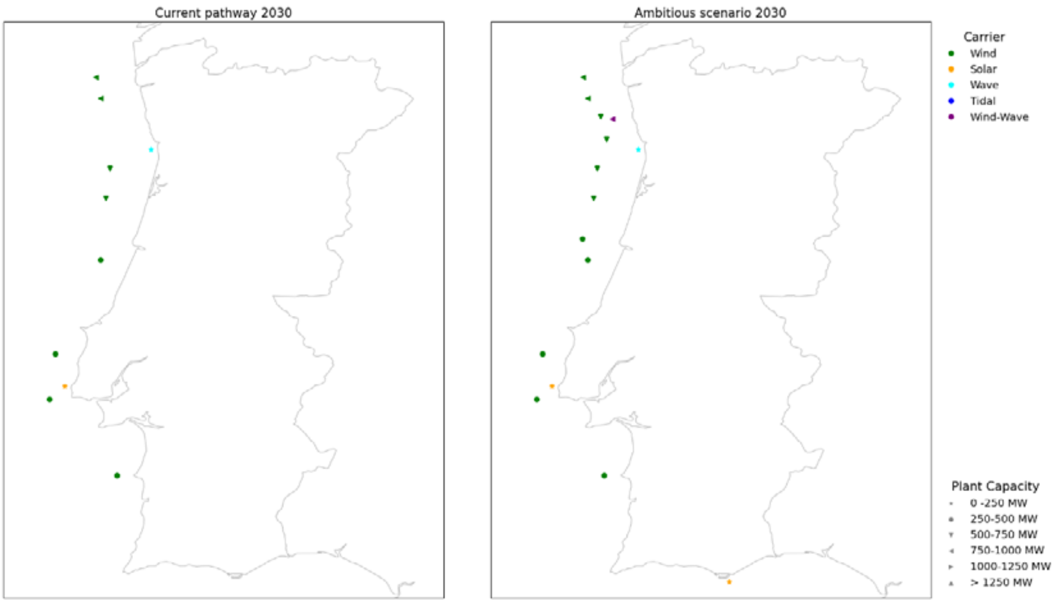


Figure 112: 2030 Scenarios for Portugal

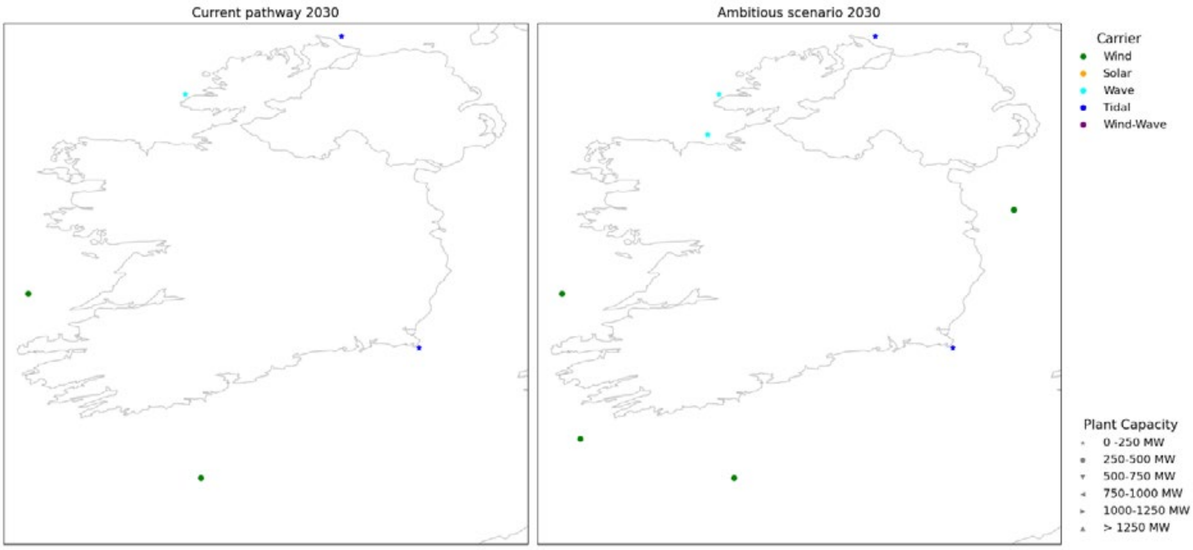


Figure 113: 2030 Scenarios for Ireland

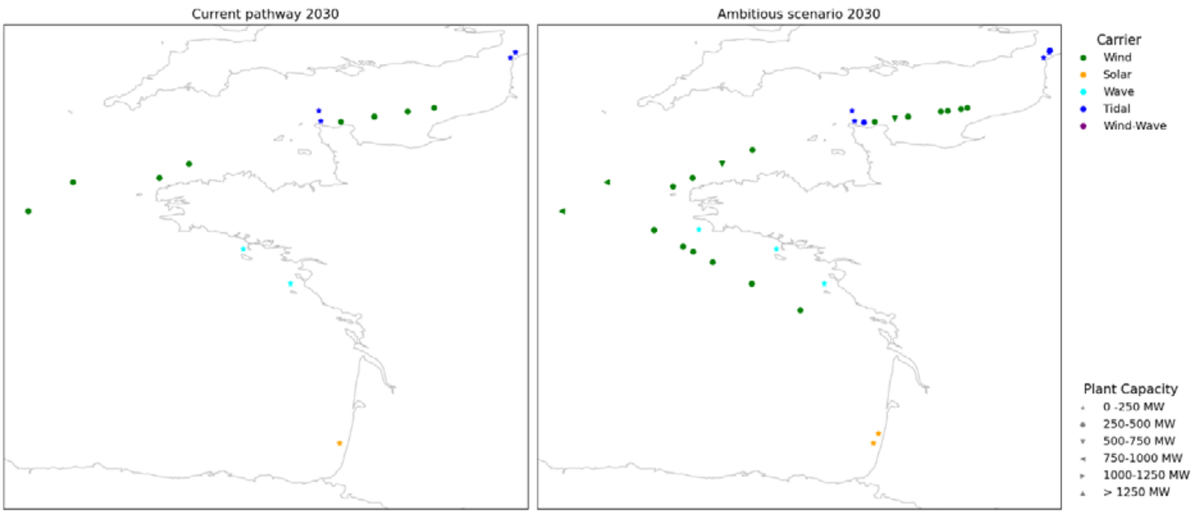


Figure 114: 2030 Scenarios for France

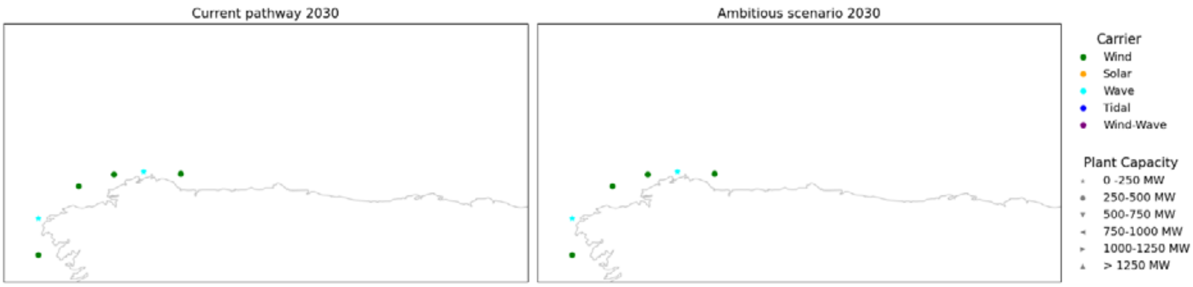
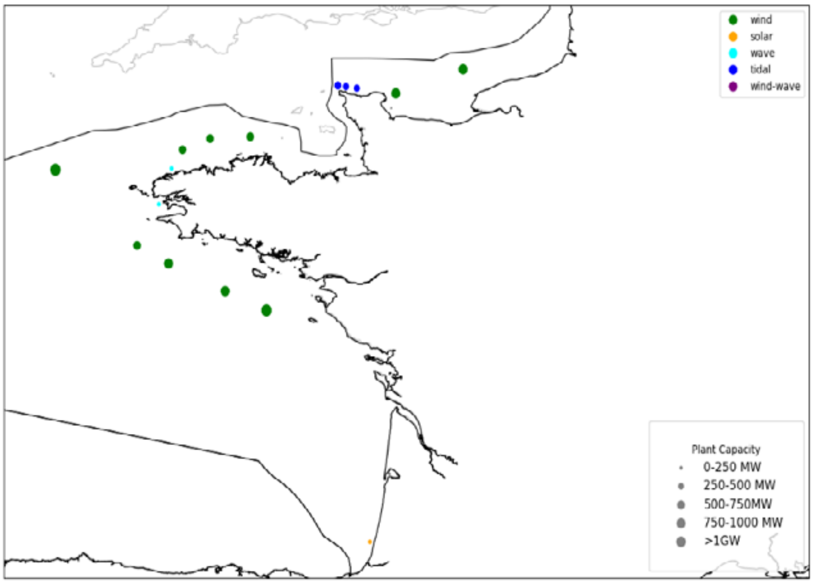
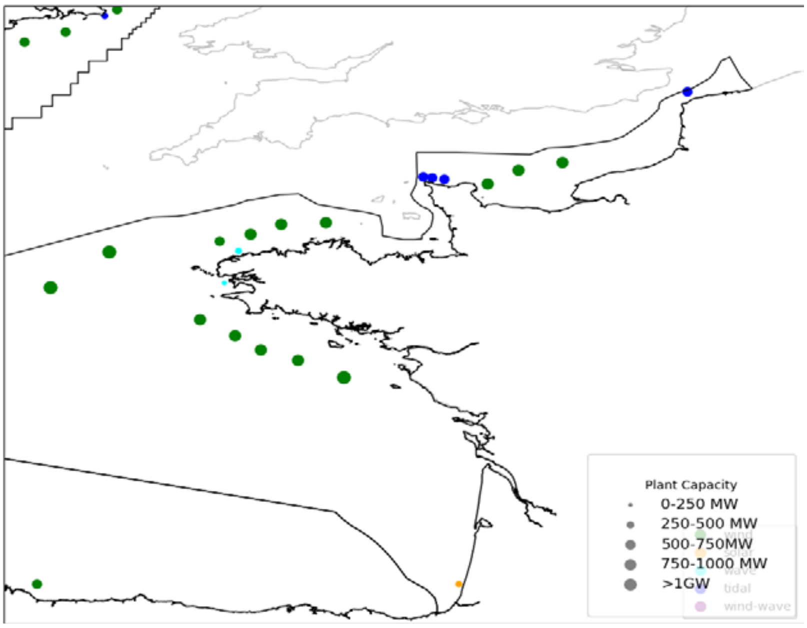


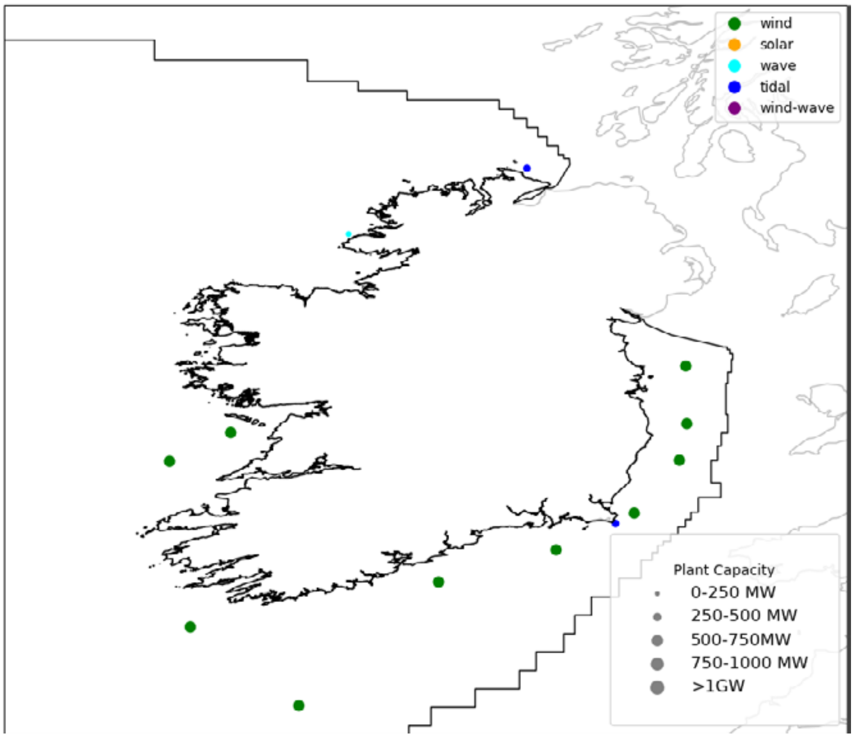
Figure 115: 2030 Scenarios for Spain



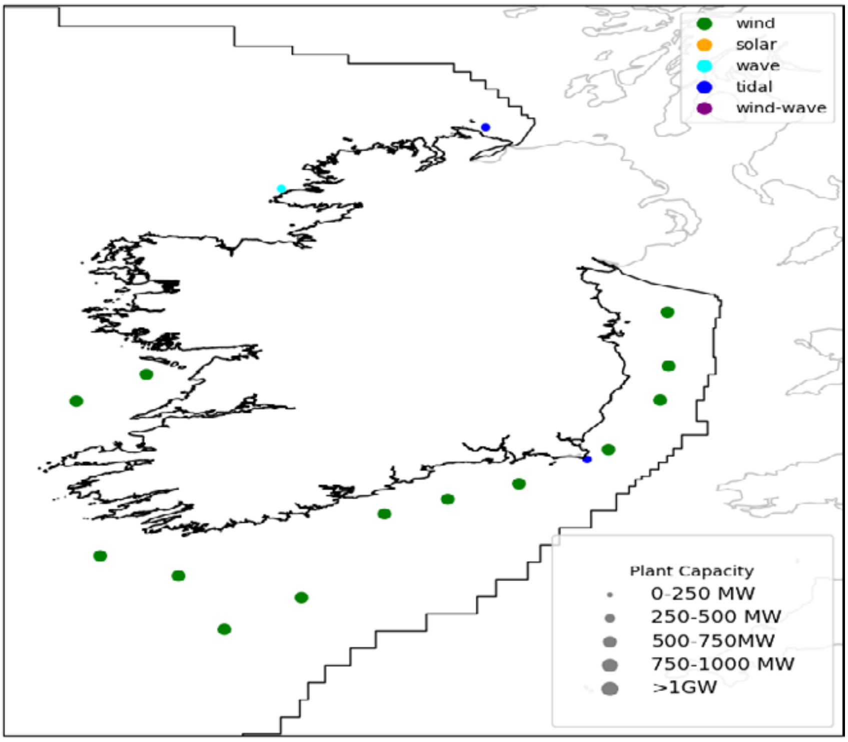
2030 CONSERVATIVE OFFSHORE PRODUCTION SCENARIO FOR FRANCE'S ATLANTIC REGION



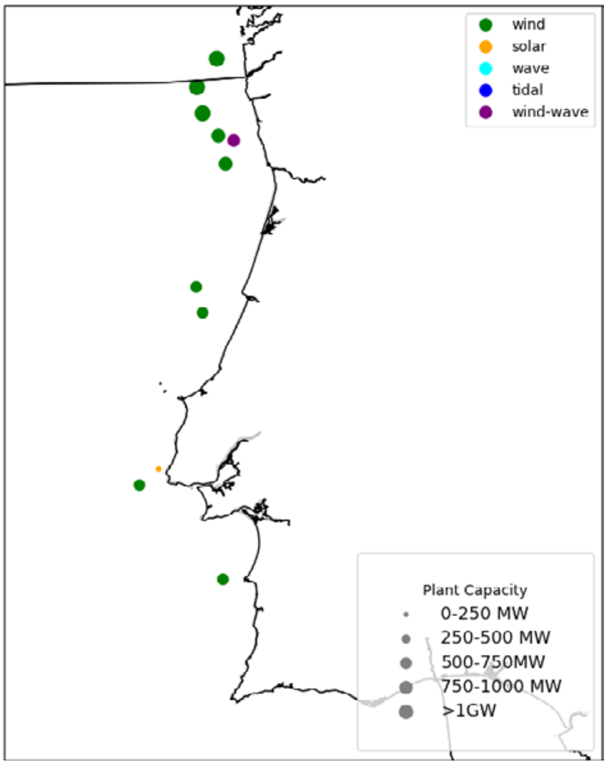
2030 AMBITIOUS OFFSHORE PRODUCTION SCENARIO FOR FRANCE'S ATLANTIC REGION



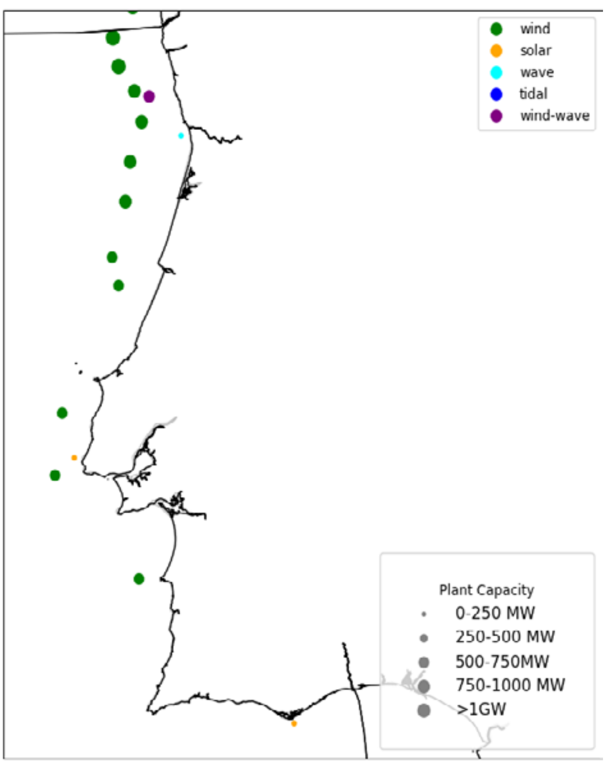
2030 CONSERVATIVE OFFSHORE PRODUCTION SCENARIO FOR IRELAND



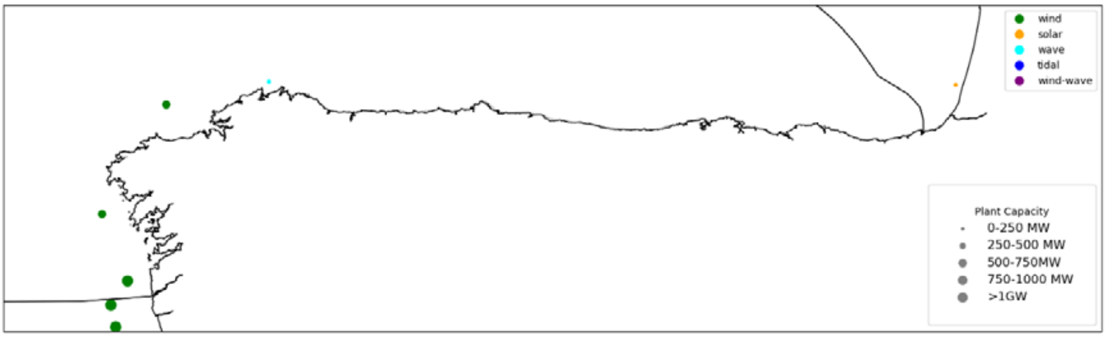
2030 AMBITIOUS OFFSHORE PRODUCTION SCENARIO FOR IRELAND



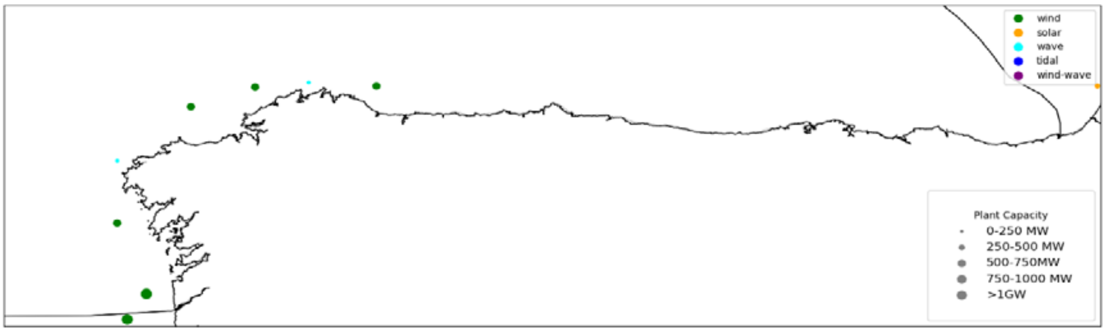
2030 Conservative Offshore Production Scenario for Portugal's Atlantic Region



2030 Ambitious offshore Production Scenario for Portugal's Atlantic Region



2030 Conservative Offshore Production Scenario for Spain's Atlantic Region



2030 Ambitious Offshore Production Scenario for Spain's Atlantic Region

A4.2 2050 Production scenarios per country

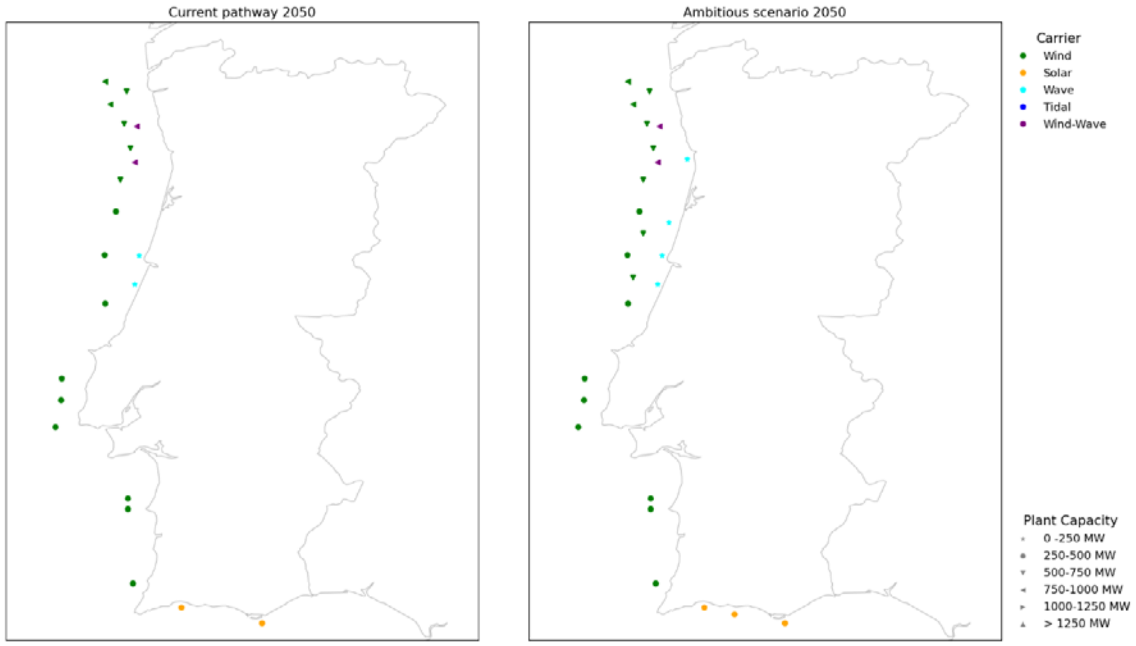


FIGURE 116: 2050 SCENARIOS FOR PORTUGAL

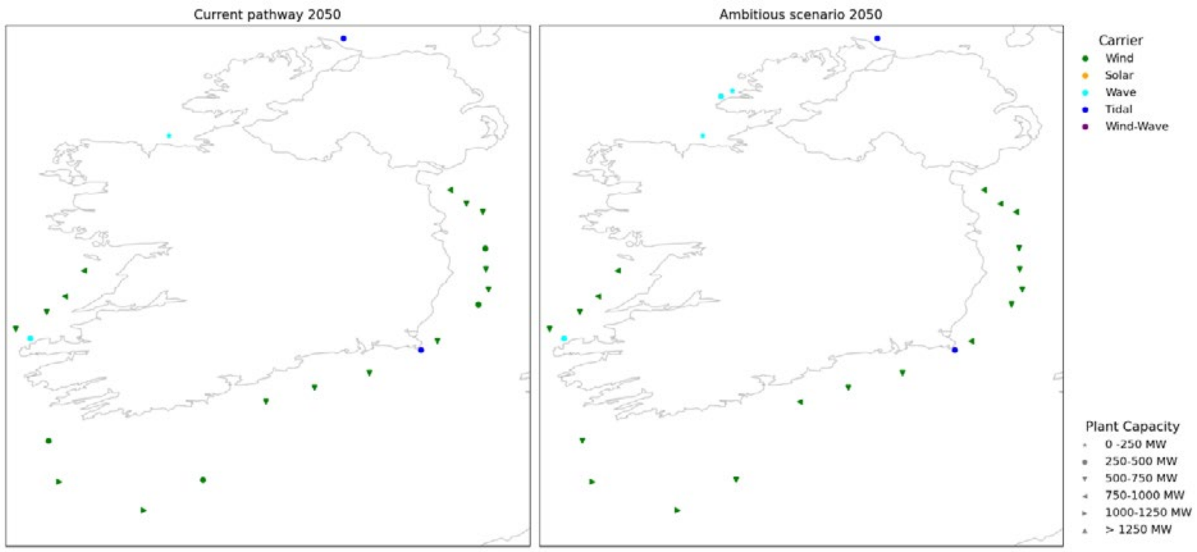


FIGURE 117: 2050 SCENARIOS FOR IRELAND

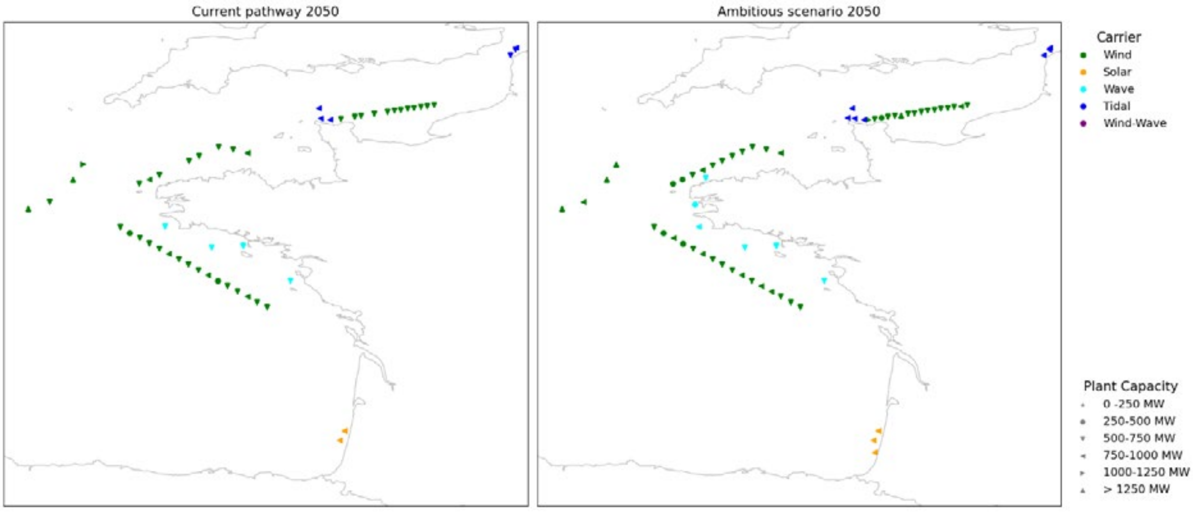


FIGURE 118: 2050 SCENARIOS FOR FRANCE

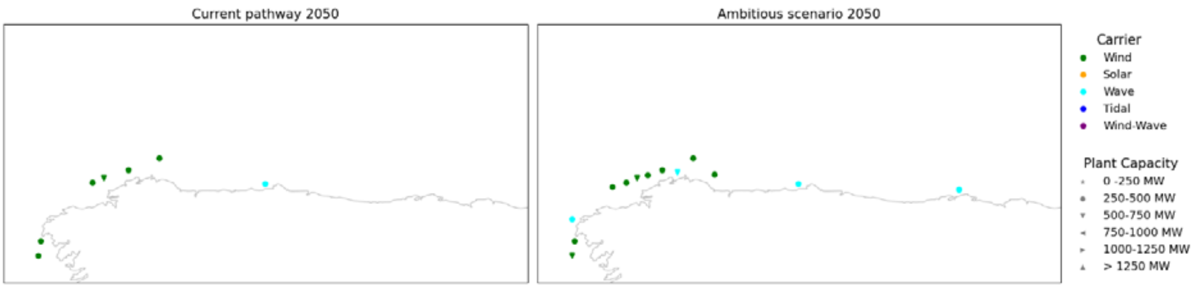
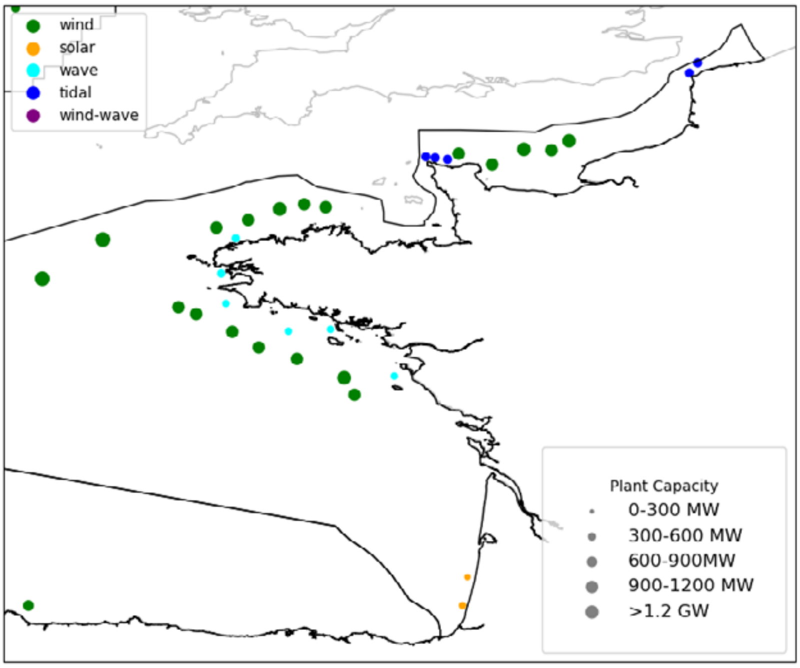
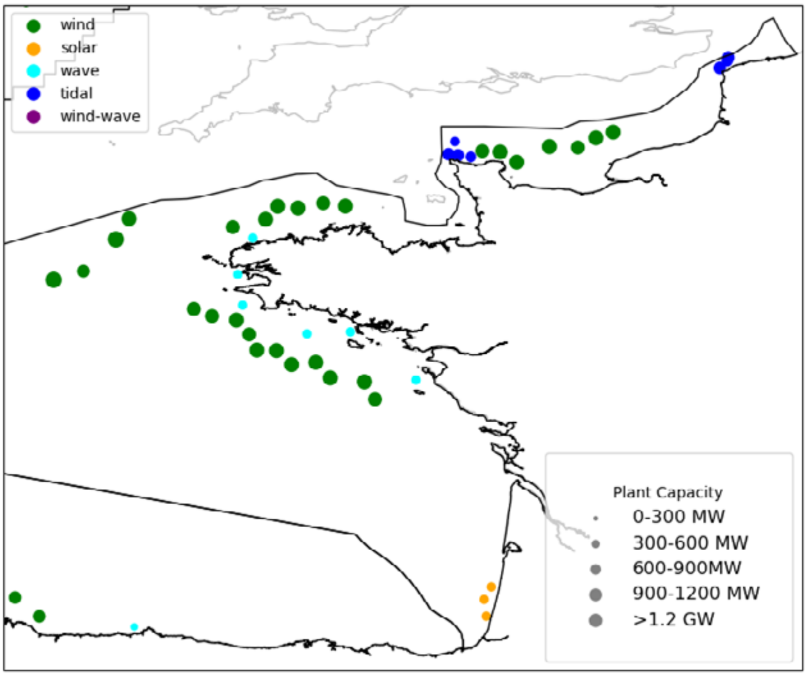


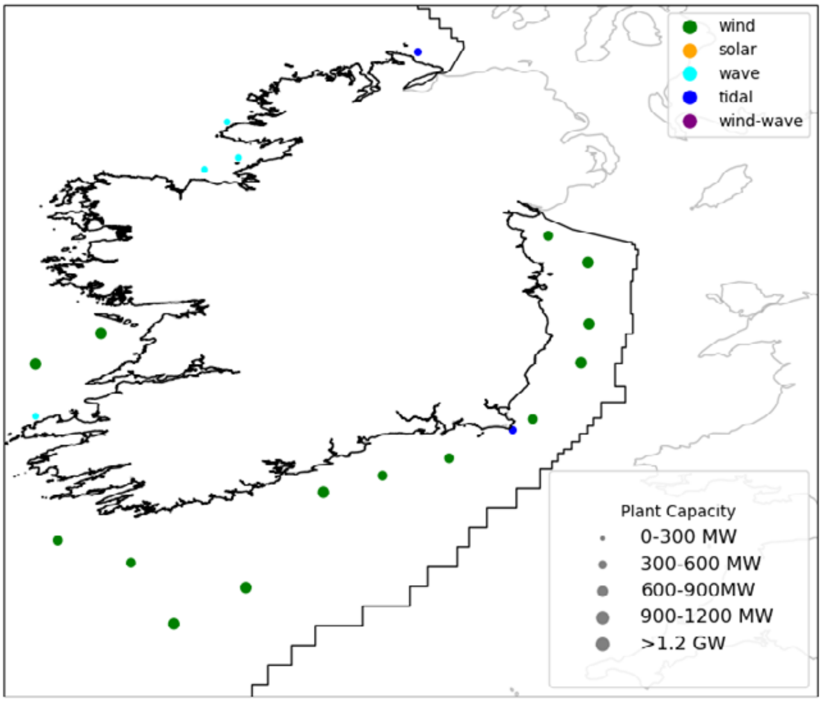
FIGURE 119: 2050 SCENARIOS FOR SPAIN



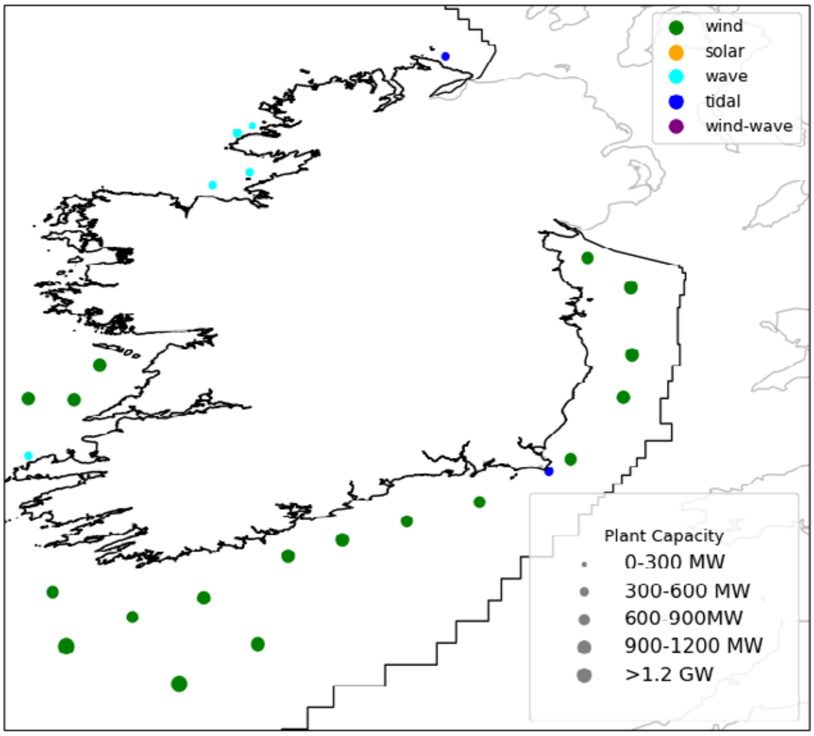
2050 CONSERVATIVE OFFSHORE PRODUCTION SCENARIO FOR FRANCE'S ATLANTIC REGION



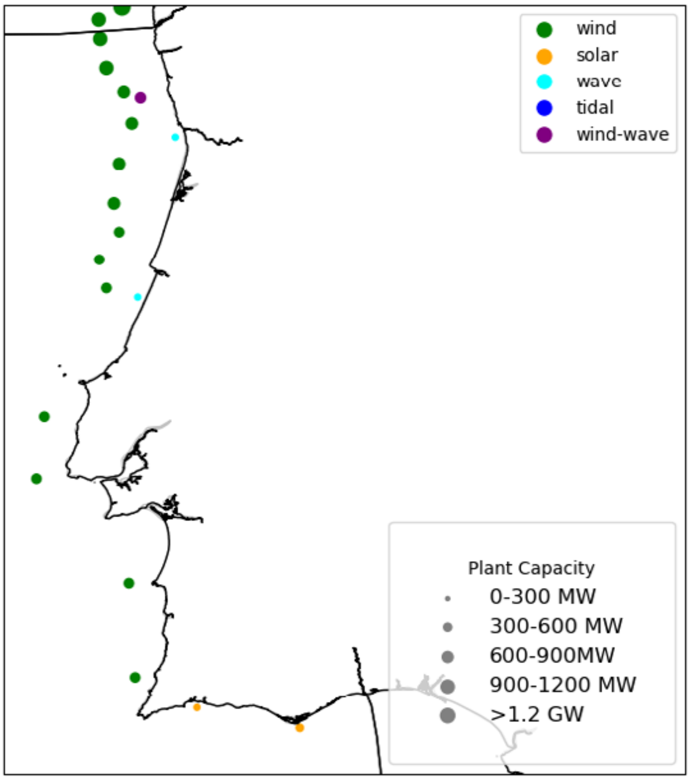
2050 AMBITIOUS OFFSHORE PRODUCTION SCENARIO FOR FRANCE'S ATLANTIC REGION



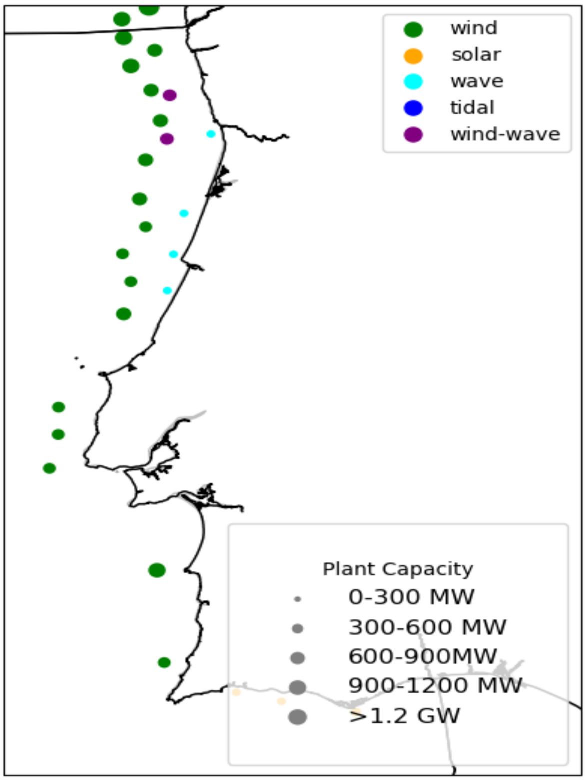
2050 Conservative Offshore Production Scenario for Ireland



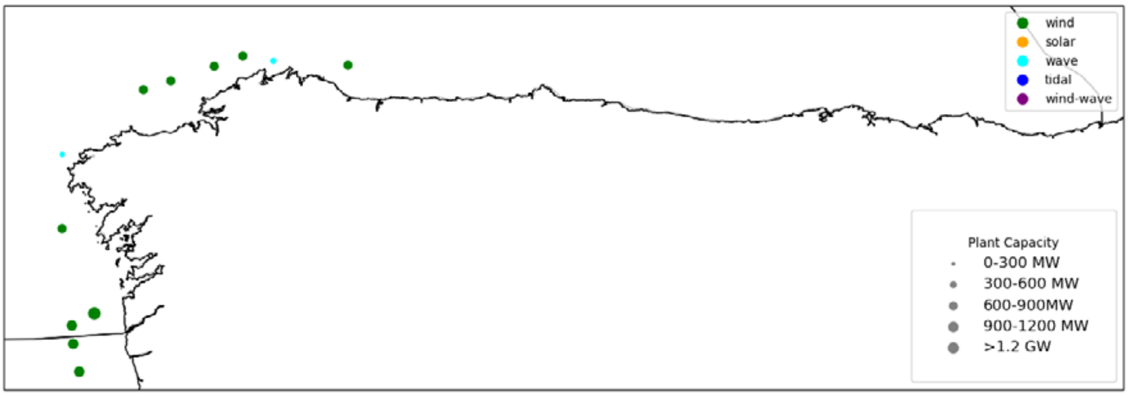
2050 Ambitious Offshore Production Scenario for Ireland



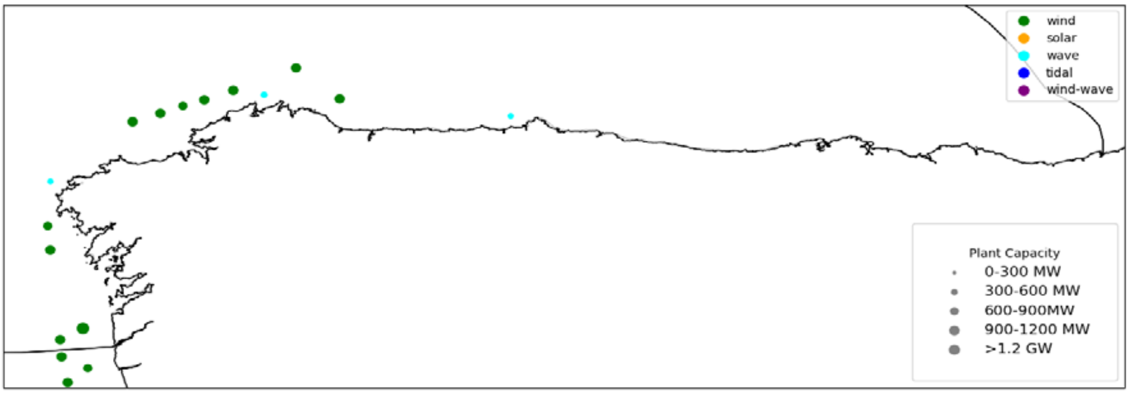
2050 CONSERVATIVE OFFSHORE PRODUCTION SCENARIO FOR PORTUGAL'S ATLANTIC REGION



2050 AMBITIOUS OFFSHORE PRODUCTION SCENARIO FOR PORTUGAL'S ATLANTIC REGION



2050 CONSERVATIVE OFFSHORE PRODUCTION SCENARIO FOR SPAIN'S ATLANTIC REGION



2050 Ambitious Offshore Production Scenario for Spain's Atlantic Region

APPENDIX 5

A5. Cost catalogue for Task 3

HVDC CAPEX, from (Cole, Martinot, Rapoport, Papaefthymiou, & Gori, 2014)			
COMPONENT	**COST**		**REMARK**
DC platform	111.3	M€/unit	1
HVDC station VSC 500 MW 300 kV	83.5	M€/unit	1
HVDC station VSC 850 MW 320 kV	101.5	M€/unit	1
HVDC station VSC 1250 MW 500 kV	135.5	M€/unit	1
HVDC station VSC 2000 MW 500 kV	170	M€/unit	1
2x1x300mm² cu ±320 kV DC Offshore	600	€/m	
2x1x1000mm² cu ±320 kV DC Offshore	1000	€/m	2
2x1x2500mm² cu ±320 kV Offshore	1324	€/m	
2x1x1500mm² cu ±500 kV Offshore	1120	€/m	
2x1x2500mm² cu ±500 kV Offshore	1468	€/m	
2x1x500mm² alu ±320 kV Onshore	546	€/m	
2x1x2400mm² alu ±320 kV Onshore	750	€/m	
2x1x1500mm2 alu ±500 kV Onshore	858	€/m	
2x1x2500mm2 alu ±500 kV Onshore	1000	€/m	
Offshore cable installation cost	400	€/m	
Onshore cable installation cost	150	€/m	3
HVAC CAPEX, from (Cole, Martinot, Rapoport, Papaefthymiou, & Gori, 2014)			
COMPONENT	**COST**		**REMARK**
AC Platform	45.5	M€/unit	1
Transformation	10.000	€/MVA	
220 kV switchgear	2.68	M€/unit	
1x3x400mm² cu 220kV Offshore	540	€/m	
1x3x1600mm² alu 220 kV Offshore	875	€/m	

2x3x1600mm² alu 220 kV Offshore	1.750	€/m	
3x3x1600mm² alu 220 kV Offshore 2	625	€/m	
3x1x1200mm² alu 220 kV Onshore	525	€/m	
3x1x1400mm² alu 220 kV Onshore	550	€/m	
3x1x2000mm² alu 220 kV Onshore	625	€/m	
6x1x1200mm² alu 220 kV Onshore	1.050	€/m	
6x1x1400mm² alu 220 kV Onshore	1.100	€/m	
6x1x2000mm² alu 220 kV Onshore	1.250	€/m	
9x1x1400mm² alu 220 kV Onshore	1.650	€/m	
9x1x2000mm² alu 220 kV Onshore	1.875	€/m	
Offshore cable installation cost	400	€/m	
Onshore cable installation cost	150	€/m	3
Reactive compensation	63.250	€/MVA	4

APPENDIX 6

N°	title	Publication year	authors	source	source_doi
1	Policy Perspective: Externalities of Developing Floating Offshore Wind Turbines	2022	Schwartz	Biden School of Public Policy & Administration	https://udspace.udel.edu/handle/19716/30921
2	Fishing within offshore wind farms in the North Sea: Stakeholder perspectives for multi-use from Scotland and Germany	2022	Schupp et al	Journal of Environmental Management	https://doi.org/10.1016/j.jenvman.2020.111762
3	Game-Theoretic Methodology and Simulation of Renewable Energy Subsidy Auctions for Preparing Bid Strategy	2022	Kell et al	Research Gate	http://dx.doi.org/10.13140/RG.2.2.35266.07368
4	Market Needs, Opportunities and Barriers for the Floating Wind Industry	2022	Diaz et al	Marine Science and Engineering	https://doi.org/10.3390/jmse10070934
5	The Atlantic surfclam fishery and offshore wind energy development: 2. Assessing economic impacts	2022	Scheld et al	ICES Journal of Marine Science	DOI: 10.1093/icesjms/fsac109
6	The Case for Policy in Developing Offshore Wind: Lessons from Norway	2022	Dahl et al	Energies	https://doi.org/10.3390/en15041569
7	Offshore wind decommissioning: an assessment of the risk of operations	2022	Shafiee and Adedipe	International Journal of Sustainable Energy	https://doi.org/10.1080/14786451.2021.2024830
8	Island in the Sea: The prospects and impacts of an offshore wind power hub in the North Sea	2022	Jansen et al	Advances in Applied Energy	https://doi.org/10.1016/j.adapen.2022.100090
9	A systematic review of barriers to greenfield investment in decarbonisation solutions	2022	Emodi et al	Renewable and Sustainable Energy Reviews	https://doi.org/10.1016/j.rser.2022.112586
10	Does participation in knowledge networks facilitate market access in global innovation systems? The case of offshore wind	2021	Tsouri et al	Research policy	https://doi.org/10.1016/j.respol.2021.104227

11	Regionally extended shared socioeconomic pathways for the offshore wind industry in Finland	2022	Jenkins et al	Energy, Ecology and Environment	https://doi.org/10.1007/s40974-022-00252-7
12	Offshore Wind Energy Policy Trends in Denmark and Germany	2022	Armagann Canan	SSRN	https://dx.doi.org/10.2139/ssrn.4060754
13	Developing local industries and global value chains: The case of offshore wind	2022	Loos et al	Technological Forecasting and Social Change	https://doi.org/10.1016/j.techfore.2021.121248
14	Winds of change: examining attitude shifts regarding an offshore wind project	2022	Bingaman et al	Journal of Environmental Policy & Planning	https://doi.org/10.1080/1523908X.2022.2078290
15	Seabirds and Marine Renewable Energy Sources	2022	Harwood and King	Seabird Biodiversity and Human Activities	https://doi.org/10.1201/9781003047520
16	A Review of Modeling Approaches for Understanding and Monitoring the Environmental Effects of Marine Renewable Energy	2022	Buenau et al	Journal of marine Science and Engeeering	https://doi.org/10.3390/jmse10010094
17	Managing Technology Transfer Challenges in the Renewable Energy Sector within the European Union	2022	Kulkanii et al	Wind	https://doi.org/10.3390/wind2010009
18	A Framework for Effective Science Communication and Outreach Strategies and Dissemination of Research Findings for Marine Energy Projects	2022	Gunn et al	Journal of marine Science and Engeeering	https://doi.org/10.3390/jmse10020130
19	Potential opportunities of multi-use blue economy concepts in Europe	2022	Ramos et al	Trends in Maritime Technology and Engineering Volume 2	https://doi.org/10.1201/9781003320289
20	European Energy Regulatory, Socioeconomic, and Organizational Aspects: An Analysis of Barriers Related to Data-Driven Services across Electricity Sectors	2022	Psara et al	Energies	https://doi.org/10.3390/en15062197
21	Empirical Evidence from OECD and BRICS Countries on the Impact of Investor Behavior on Renewable Energy Deployment	2022	Killinc Ata and Dolmatov	Research Square	https://doi.org/10.21203/rs.3.rs-1599984/v1
22	Can artificial magnetic fi elds alter the functional role of the	2022	Albert et al	marine Biology	https://doi.org/10.1007/s00227-022-04065-4

	blue mussel, Mytilus edulis?				
23	Combining wind power and farmed fish: Coastal community perceptions of multi-use offshore renewable energy installations in Europe	2022	Billing et al	Energy reseach & Social Science	https://doi.org/10.1016/j.erss.2021.102421
24	Sustainable development of renewable energy integrated power sector: Trends, environmental impacts, and recent challenges	2022	All-Shetwi	Science of the Total Environment	https://doi.org/10.1016/j.scitotenv.2022.153645
25	Beyond LCOE: A multi-criteria evaluation framework for offshore renewable energy projects	2022	Vanegas-Cantarero	Renewable and Sustainable Energy Reviews	https://doi.org/10.1016/j.rser.2022.112307
26	The Energy Transition and the Changing Nature of Governance: Analyzing Evidence from the European Union and the Gulf Cooperation Council	2022	Guerra and Atalay	Developement	https://doi.org/10.1057/s41301-021-00295-z
27	A Summary of Environmental Monitoring Recommendations for Marine Energy Development That Considers Life Cycle Sustainability	2022	Amerson et al	Journal of marine Science and Engeeering	https://doi.org/10.3390/jmse10050586
28	Site selection of floating offshore wind through the levelised cost of energy: A case study in Ireland	2022	Martinez and Iglesias	Energy Conversion and Management	https://doi.org/10.1016/j.enconman.2022.115802
29	A review of methods and indicators used to evaluate the ecological modifications generated by artificial structures on marine ecosystems	2022	Taormina et al	Journal of Environmental Management	https://doi.org/10.1016/j.jenvman.2022.114646
30	Aspects of blue economy in the Baltic Sea region	2022	Pöntynen Riitta	Baltic Sea Region Policy Briefing series	ISSN: 2342-3153 centrumbalticum.org/files/5230/BSR_Policy_Briefing_5_2022.pdf
31	Triton Field Trials: Promoting Consistent Environmental Monitoring Methodologies for Marine Energy Sites	2022	Eaves et al	Journal of marine Science and Engeeering	https://doi.org/10.3390/jmse10020177
32	Harvesting Energy from Ocean: Technologies and Perspectives	2022	Khan et al	Energies	https://doi.org/10.3390/en15093456

33	A review of marine stressors impacting Atlantic salmon Salmo salar, with an assessment of the major threats to English stocks	2022	Gillson et al	Reviews in Fish Biology and Fisheries	https://doi.org/10.1007/s11160-022-09714-x
34	The next frontier: Human settlements in the marine environment	2022	Mastrantonis and Dubininkasc	Future	https://doi.org/10.1016/j.futures.2022.102953
35	Overlooked factors in predicting the transition to clean electricity	2022	Martin et al	Environmental Research: Infrastructure and Sustainability	http://iopscience.iop.org/article/10.1088/2634-4505/ac70f7
36	Wave energy converters in low energy seas: Current state and opportunities	2022	Foteinis	Renewable and Sustainable Energy Reviews	https://doi.org/10.1016/j.rser.2022.112448
37	Agreements and benefits in emerging ocean sectors: Are we moving towards an equitable Blue Economy?	2022	Cisneros-Montemayor et al	Ocean & Coastal Management	https://doi.org/10.1016/j.ocecoaman.2022.106097
38	Tracking Seabirds for Conservation and Marine Spatial Planning	2022	Pereira et al	Seabird Biodiversity and Human Activities	https://doi.org/10.1201/9781003047520
39	Marine Online Platforms of Services to Public End-Users—The Innovation of the ODYSSEA Project	2022	Nezhad et al	Remote sensing	https://doi.org/10.3390/rs14030572
40	IEA Wind White Paper: Cumulative Effects Analysis for Wind Energy Development: Current Practices, Challenges, and Opportunities.	2022	Gill and Hein	IEA Wind White Paper	https://doi.org/10.2172/1855171
41	Balancing profitability of energy production, societal impacts and biodiversity in offshore wind farm design	2022	Renewable and Sustainable Energy Reviews	Virtanen et al	https://doi.org/10.1016/j.rser.2022.112087
42	How blue financing can sustain ocean conservation and development: A proposed conceptual framework for blue financing mechanism	2022	Shiiba et al	Marine Policy	https://doi.org/10.1016/j.marpol.2021.104575
43	Mining the Deep: Can the Law “Get It Right” with Balancing the Environment and Resource Extraction through Environmental Impact Assessments?	2022	Robertson et al	Ocean Yearbook Online	https://doi.org/10.1163/22116001-03601007
44	Investigating avoidance and attraction responses in lesser black-backed	2022	Johnston et al	Marine Ecology Progress Series	https://doi.org/10.3354/meps13964

	gulls Larus fuscus to offshore wind farms				
45	Enabling conditions for effective marine spatial planning	2022	Zuercher et al	Marine Policy	https://doi.org/10.1016/j.marpol.2022.105141
46	Which policy instruments promote innovation in renewable electricity technologies? A critical review of the literature with a focus on auctions	2022	Del Rio and Kiefer	Energy reseach & Social Science	https://doi.org/10.1016/j.erss.2022.102501
47	Marine Spatial Planning: Assessment of the intensity of conflicting activities in the marine environment of the Aegean Sea	2022	Pataki and Kitsiou	Ocean & Coastal management	https://doi.org/10.1016/j.ocecoaman.2022.106079
48	Marine Spatial Planning in Regional Ocean Areas: Trends and Lessons Learned	2022	McArteer et al	Ocean Yearbook Online	https://doi.org/10.1163/22116001-03601013
49	The Interplay Between EU Law and Regional Sea Conventions: Shaping Environmental Protection in Relation to Offshore Energy Production Across Europe?	2022	Giannopoulos	European Energy and Environmental Law Review	http://www.kluwerlawonline.com/api/Product/CitationPDFURL?file=Journals\EELR\EELR2022001.pdf
50	Imagining the Invisible: Spatial Design for the North Sea	2022	Couling	Planning Practice & Research	https://doi.org/10.1080/02697459.2022.2026679
51	Deep aspirations: towards a sustainable offshore Blue Economy	2022	Novaglio et al	Reviews in Fish Biology and Fisheries	https://doi.org/10.1007/s11160-020-09628-6
52	Contested climate policies and the four Ds of public participation: From normative standards to what people want	2022	Perlaviciute	WIREs Climate Change	https://doi.org/10.1002/wcc.749
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