COMPREHENSIVE STUDY ON FLOATING OFFSHORE WIND POTENTIAL OFF THE IRISH COAST

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ABSTRACT

This work is a diligent inventory of the waters around Ireland to assess their potential for accommodating floating offshore wind farms. It summarizes all current constraints that could impact development while also identifying areas where the installation and operation of floating offshore wind farms would pose the highest risk for the project. The methodology presented in this study is not confined to floating wind technology and is transferable to other forms of offshore renewable energy projects, including wave and tidal energy. Following careful consideration of 34 constraints, a map has been created to illustrate the feasible locations for deploying floating offshore wind farms. The resulting area accounts for only 18.3% of the originally surveyed area of the exclusive economic zone. Calculations of the installed power density, gross annual energy yield and capacity factor are based on theoretical DTU 10-MW wind turbine. The power capacity that potentially could be installed in two analysed layout scenarios is respectively 328 GW or 410 GW. These figures are over 26 times the total installed capacity in Ireland considering all conventional and renewable energy sources. The efficiency of the reference wind turbine expressed as a capacity factor, is in the range of 56.7% to 64.1% and the gross annual energy output is between 53 and 60 GWh/year/turbine.

INTRODUCTION

The instability and reduction in energy supplies, coupled with the escalating energy demand, have underscored the necessity for advancing large-scale offshore wind projects with high capacity (International Renewable Energy Agency, 2019). Transparent and predictable legislation plays a pivotal role in facilitating energy diversification (Dagar et al., 2024). The policy change was initiated at the Paris Climate Conference (COP21). The agreement reached there, known as the Paris Agreement, is a legally binding arrangement involving close to 190 Parties. The objective is to limit global warming, and in order to achieve it, the developed countries committed to reducing greenhouse gas emissions and supporting developing countries by building their resilience to climate change (UN Climate Change Conference (COP21), 2015). Dependency on energy import may significantly decrease energy security (De Rosa et al., 2022), therefore the goal is not only to reduce emissions but also to increase energy security. The diversification of energy sources in the long term also contributes to the economic well-being of developed countries (Gozgor & Paramati, 2022), thereby bolstering political stability and their influence in the global economy. Many countries have implemented national regulations to streamline development. Ireland has already commenced legislative changes to unlock the potential of Ireland's offshore wind energy. The broad guidelines have been set in The Maritime Planning Act (Government of Ireland, 2021a) and the National Marine Planning Framework (Government of Ireland, 2021b). The directions of where Offshore Renewable Energy (ORE) should be deployed in Irish waters have been studied in the Offshore Renewable Energy Development Plan (OREDP) (Government of Ireland, 2014) published in 2014 and its successor the second Offshore Renewable Energy Development Plan (OREDP II) (Department of the Environment, 2023a) that is still in the draft version. Ireland has great potential to develop offshore wind energy projects. In 2004, Ireland commissioned its first and so far only offshore wind farm Arklow Bank. Despite having great wind resources and experience, the effort to deliver more projects was discontinued. Now Ireland is back on the track of offshore wind, having 77 projects in the pipeline of development (Offshore Market Intelligence & Marine Cable Consulting, 2024). In May of 2023, four offshore wind projects won the first Irish Offshore Renewable Energy

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Support Scheme auction (Department of the Environment, 2023b). The total installed capacity of winning offshore wind projects is 3,074 MW and the average price of successful offers is €86.05/MWh. It is worth noting that the most advanced projects are based on fixed bottom offshore wind technology, the Floating Offshore Wind (FOW) projects are still in the early phase of development. A deep-rooted relationship with the sea has shaped Irish culture and history, therefore responsible planning and public support are crucial for the development of offshore wind projects. The fishery is not only important for local communities but is also a vital part of the Irish economy, adding four per cent to the gross domestic product (Ireland's Seafood Development Agency, 2024). A recent study of public perception of offshore wind farms in Ireland shows that in the opinion of most Irish citizens, the government is not doing enough to combat climate change by reducing emissions and investing in offshore wind (Cronin et al., 2021). The 87% of those surveyed would support actively, or not object to the commissioning of new offshore wind farms in their locality. Whereas 93% of respondents would facilitate the construction of offshore wind farms outside of their locality (Cronin et al., 2021). The analyses of the conflicts with the communities and sea users conducted independently in the United States of America and South Korea by (Bidwell et al., 2023) and (Park et al., 2024) suggest that an important role in the attitude towards offshore wind has values, experiences and positions upheld within communities, not necessarily facts or mitigation measures taken by developers. Also, participation in the planning process and feeling of justice and recognition are crucial elements that shape the perception. Therefore, the investors and governments shall implement new strategies of planning. A review of international literature and legislation as well as the consideration of industry requirements and best practices have shaped the presented methodology. It focused not only on the spatial planning perspective but also on commercial aspects of Floating Offshore Wind Farm (FOWF) development, construction and operation. This study excludes the areas that have unfavourable characteristics and have a conflicting use. This is intended to act as a starting point for a more detailed site selection process where potential sites are ranked relative to each other. The case study focuses on FOW in Irish waters nonetheless the methodology could equally be applied to other ORE technologies. Moreover, other regions could be explored with the same methodology provided suitable data is available. As a result of the applied methodology, the areas feasible for FOW deployment have been presented, as well as the power capacity and efficiency of the Wind Turbine Generator (WTG) in specific locations. Figure 1, depicts the outline of the applied methodology for FOWF.

1 METHODOLOGY

1.1 Dedicated tools

The Geographic Information System (GIS) allows for the organising, management and processing of data in a spatial domain. It has two main applications, the first represents its primary purpose to serve as a geographically referenced information database. The second is to be used as an analytical tool where interactions between data create additional information augmenting existing databases, that can be depicted as derivate layers of maps, statically analysed, or be input for Multi-criteria Decision Making methods (Eastman et al., 1995). The second application where the system is not only a statical database but a dynamic analytical tool creating added value is the real strength of GIS. The shift from a database to an analytical tool created many additional functionalities and methods of data processing and analysis, as well as underpinning the development of new software that uses some of the GIS outputs. Due to the spatial character of the research, the GIS software has been used to process and analyse data in this study. The adopted methodology is based on the literature review in the field of offshore wind energy spatial planning and site selection, including governmental studies on spatial development plans for offshore wind energy. The methodology implemented in the OREDP and OREDP II, as well as spatial analysis for the Celtic Sea off the southwest coast of England and Wales (Fitch-Roy et al., 2020; The Crown Estate, 2022), were reviewed and considered in this study. Moreover, the academic research studies conducted for various regions were reviewed. That included spatial investigation of sites off the Spanish coast (Castro-Santos et al., 2020), off the coast of Portugal, Spain and France (Díaz & Guedes Soares, 2020), off the coast of Morocco (Taoufik & Fekri, 2021), Grece (Vagiona & Kamilakis, 2018) and the USA (Beiter et al., 2016). A diligent review of relevant studies in the field has been conducted separately as a part of the ongoing research programme and can be accessed through the following publication (Szczepaniec et al., 2024).

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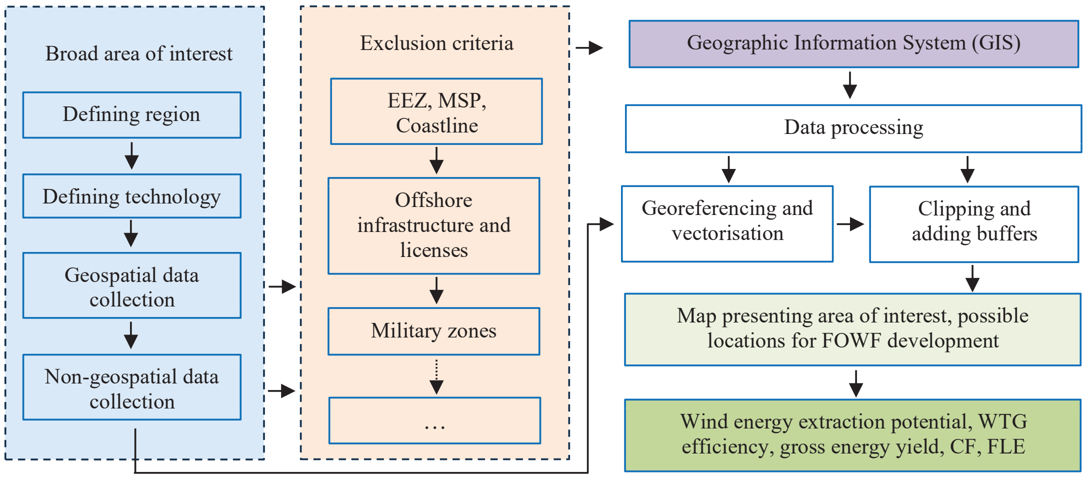

Figure 1: Flowchart, adopted methodology for FOWF site selection

1.2 Defining region

The initial step is a definition of the broad area of interest. The current study is focused on Irish waters, therefore the limitation of the investigated area is the Exclusive Economic Zone (EEZ), where the jurisdiction and rights of the coastal State are regulated by the United Nations Convention (United Nations Convention, 1982). Moreover, the area was further restricted to a distance of 200 km from the Irish coast to account for the extensive cable connection cost and the large distance for maintenance access (Díaz & Guedes Soares, 2020; The Crown Estate, 2022).

1.3 Defining technology

This research is focused on FOW. The Irish waters due to their favourable bathymetry and abundance of wind resources are naturally suited to host this technology. The chosen technology defines the set of data to be acquired and the exclusion criteria due to its specific technical requirements. Based on available literature and regulations, (Beiter et al., 2016; Castro-Santos et al., 2020; Department of the Environment, 2023a; Díaz & Guedes Soares, 2020; Martinez & Iglesias, 2022) there are various water depth ranges suitable for FOW deployment, typically falling within the range of 50 m to 1000 m. The OREDP II (Department of the Environment, 2023a) defined the desirable range of sea depth of 60-1,000 m. The same assumption has been made in this study.

1.4 Data collection

Data types that have been used in the study can be divided into two main groups:

1- Geospatial data- contains the information about the physical object, phenomena or other information that is represented in geographic coordinates;
2- Non-geospatial data- data that have no geographical reference, and is used after processing in the study, e.g. limitation of water depth for FOW or maximal distance from shore.

The geospatial data usage allows for conducting the spatial analysis that is based on the geographical relation of the features. The vast majority of the geospatial data required for the study is freely available on the internet for public good research purposes. However, usage of the data for commercial applications may have some restrictions. The Directive 2007/2/EC of the European Parliament and the Council has regulated and commenced establishing a geospatial information database to support environmental policies. The program and portal are called Infrastructure for Spatial Information in the European Community (INSPIRE) (European Parliament and of the Council, 2007). In addition to the INSPIRE database, there is also the European Marine Observation and Data Network portal gathering European marine data. The idea behind creating the data portal is to provide accurate information to

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support the development of policies and legislation as well as sustainable economic growth, "blue growth" (European Parliament and of the Council, n.d.). Along with centralised European portals, there are also national spatial information repositories such as Irland's Marine Atlas provided by the Marine Institute, Ireland's National Parks and Wildlife Service or Geological Survey Ireland. Also, national research and academic institutions, private companies and financial bodies that support investments in renewables with useful information such as the Global Wind Atlas (Global Wind Atlas, 2023) created by the Technical University of Denmark (DTU Wind Energy), the World Bank Group, and Vortex. Another example is the Modern-Era Retrospective Analysis for Research and Applications reanalysis data provided by NASA (National Aeronautics and Space Administration, 2020) and ERA5 reanalysis data provided by the ECMWF as a part of the COPERNICUS programme (European Centre for Medium-Range Weather Forecasts, n.d.). Vast geospatial data can be viewed through the integrated map-viewers accessed through an internet browser with no need to use any additional software nor of having competencies in programming. Many of those data can be accessed not only in the view mode that limits interaction and processing capabilities but also can be downloaded and stored locally on the hard drive. That opens the opportunity to conduct countless research activities and to turn them into real applications. The sources of the specific data sets utilised for the present study are detailed in subsequent sections.

1.5 Exclusion criteria

The exclusion criteria are based on the given technology technical requirements as well as the literature and legislation review. Application of exclusion criteria to GIS forms exclusion areas that represent each considered exclusion criterion. Those are the areas of unfavourable characteristics, in the broad range of factors. This includes bathymetry, ship routes, exploitation licenses and more, as listed in Table 1. For instance, licensed gas and oil deposits and rigs are areas where the FOWF should not be located (Díaz & Guedes Soares, 2020). Another example is the range of the water depth, where the locations with bathymetry below 60 m and over 1,000 m are considered unfavourable for FOWF deployment, therefore those areas are forming exclusion areas (Beiter et al., 2016). To account for the security and technical and project risk mitigation, some of the exclusion areas were expanded by a buffer zone. The buffer zone can be added as a result of the formal guidelines like a recommended minimum distance of 750 m on both sides from subsea power cables (European Subsea Cables Association, 2023) or binding regulations like a minimum distance of 1 NM from pipelines (Government of Ireland, 2021b). Some buffer zones are added for security reasons but are not necessarily required by law, for example, the distance of 2 NM from the cargo, tanker and passenger ships to account for the manoeuvrability (Department of the Environment, 2023a). A review of the criteria types and buffers applied by various scholars has been already conducted and can be accessed through the following publication (Szczepaniec et al., 2024). The exclusion criteria are divided into eight categories: legislative, offshore infrastructure and licenses, military zones, navigation and fishing, ship routes, sea usage and exploitation, environment, heritage, and technology. A detailed list of the applied exclusion criteria divided into categories and sub-categories is presented in Table 1.

Table 1: Exclusion criteria, spatial data layers

Category	No.	Subcategory	Unsuitable area	Buffer zone	Data source
1. Legislative	1.1	EEZ	Beyond	N/A	(Flanders Marine Institute, 2024)
	1.2	Maritime Spatial Planning (MSP)	Beyond	N/A	(Government of Ireland, 2021)
	1.3	OREDP II	Beyond	Specific to feature	(Department of the Environment, 2023)
2. Offshore infrastructure and licenses	2.1	Existing and consented ORE	Within	12xRD	(European Marine Observation and Data Network, 2023)

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Category	No.	Subcategory	Unsuitable area	Buffer zone	Data source
	2.2	ORE Test sites	Within	2 NM	(European Marine Observation and Data Network, 2023)
	2.3	Gas and oil platforms and licenses	Within	500 m	(European Marine Observation and Data Network, 2023)
	2.4	Underwater pipelines	Within	1 NM	(Marine Institute, 2022)
	2.5	Underwater Power Cables and Telecommunication	Within	750 m	(EirGrid, 2020, 2024; European Marine Observation and Data Network, 2023; Greenlink Interconnector, 2024; The Kingfisher Information Service – Offshore Renewable & Cable Awareness project, 2019)
	2.6	Exploration wells	Within	500 m	(Marine Institute, 2022)
	2.7	Meteorological equipment, navigation buoy	Within	500 m	(Marine Institute, 2022)
3. Military zones	3.1	Military training zones	Within	N/A	(European Marine Observation and Data Network, 2023)
4. Navigation and fishing, ship routes	4.1	Cargo ships	≥250 passes/year/ km^2	2 NM	(European Marine Observation and Data Network, average of 2019, 2021, 2022)
	4.2	Passenger ferries	≥250 passes/year/ km^2	2 NM	(European Marine Observation and Data Network, average of 2019, 2021, 2022)
	4.3	Tankers	≥250 passes/year/ km^2	2 NM	(European Marine Observation and Data Network, average of 2019, 2021, 2022)
	4.4	Fishing	≥52 passes/year/ km^2	N/A	(European Marine Observation and Data Network, average of 2019, 2021, 2022)
	4.5	Other: sailing, dredging, service, tug and tow, pleasure, high-speed craft, military	Nearshore, not contributing	N/A	(European Marine Observation and Data Network, average of 2019, 2021, 2022)
5. Sea usage and exploitation	5.1	Waste, sewage, munition, dredge	Within	500 m	(Environmental Protection Agency, 2023; European Marine Observation and Data Network, 2023)
	5.2	Anchorage area	Nearshore, not contributing	N/A	(Department of the Environment, 2023; UK Hydrographic, 2021)

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Category	No.	Subcategory	Unsuitable area	Buffer zone	Data source
	5.3	Traffic Separation Scheme (TSS)	Within	2 and 5 NM	(Department of the Environment, 2023; UK Hydrographic, 2021)
	5.4	Licensed aquaculture AQ	Within	N/A	(Marine Institute, 2022)
6. Environment	6.1	Special Protection Areas (SPA)	Within	2 km	(National Parks & Wildlife Service, 2024)
	6.2	Special Areas of Conservation (SAC)	Within	2 km	(National Parks & Wildlife Service, 2024)
	6.3	Natural Heritage Areas (NHA)and proposed Natural Heritage Areas (pNHA)	Within	2 km	(National Parks & Wildlife Service, 2015)
	6.4	OSPAR Declining Threatened Habitats	Within	2 km	(European Marine Observation and Data Network, 2022)
	6.5	Important Bird Areas (IBA)	Within	2 km	(BirdLife International, 2023)
	6.6	obSERVE High Density Areas	Within	2 km	(Department of the Environment, 2023)
	6.7	Herring Spawning Grounds (HSG)	Within	2 km	(Marine Institute, 2022)
7. Heritage	7.1	UNESCO World Heritage Sites	Within	5 km	(UNESCO, 2024)
	7.2	UNESCO Dublin Bay Biosphere	Within	5 km	(Dublin Bay Biosphere, 2024)
	7.3	Shipwrecks	Within	500 m	(European Marine Observation and Data Network, n.d.; Infomar, 2021)
8. Technology	8.1	Bathymetry	≤60 and ≥1000 m	N/A	(European Marine Observation and Data Network, 2022)
	8.2	Sea substrate	Rocks and boulders	N/A	(European Marine Observation and Data Network, 2021; Infomar, 2022)
	8.3	Distance to shore	≥ 200 km	N/A	(Marine Institute, 2022)
	8.4	Wind speed	N/A	N/A	(Global Wind Atlas, 2023)

2 RESULTS

The area of interest was delineated by overlaying the exclusion areas and then extracting the unconstrained region. Figure 2 presents all exclusion criteria that have been considered in the study as listed in Table 1. The broad area of interest, initially determined by the shape of the EEZ, was further restricted to a distance of 200 km from the shore. In the subsequent stage, the area was confined to the specified bathymetric extent. The additional exclusion areas were then included, as shown in Figure 4 to Figure 6, leading to the outcome illustrated in Figure 7, which presents the area of interest where the development of FOWF is possible and the project risk is relatively low. The extent of the area of interest was then utilised to estimate the total installed power capacity, WTG efficiency and average annual energy output. Figure 3, presents the long-term wind speed distribution at 100 m across the entire broad

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area of interest and the Irish landmass. The long-term average wind speed at 100 m exceeds 9 m/s on the east coast and 10 m/s on the west coast. Further into the sea, the average wind speed rises exceeding 10 m/s in some areas off the east coast, and 11 m/s far off the west of Ireland. The long-term average wind speed of 9 m/s and more is far above the standard 3-4 m/s cut-in wind speed of the modern WTG, including the DTU 10-MW Reference Wind Turbine used in this research (Bak et al., 2013). Due to the great wind potential of the entire broad area of interest, wind speed has not been considered as the exclusion criterion in this study.

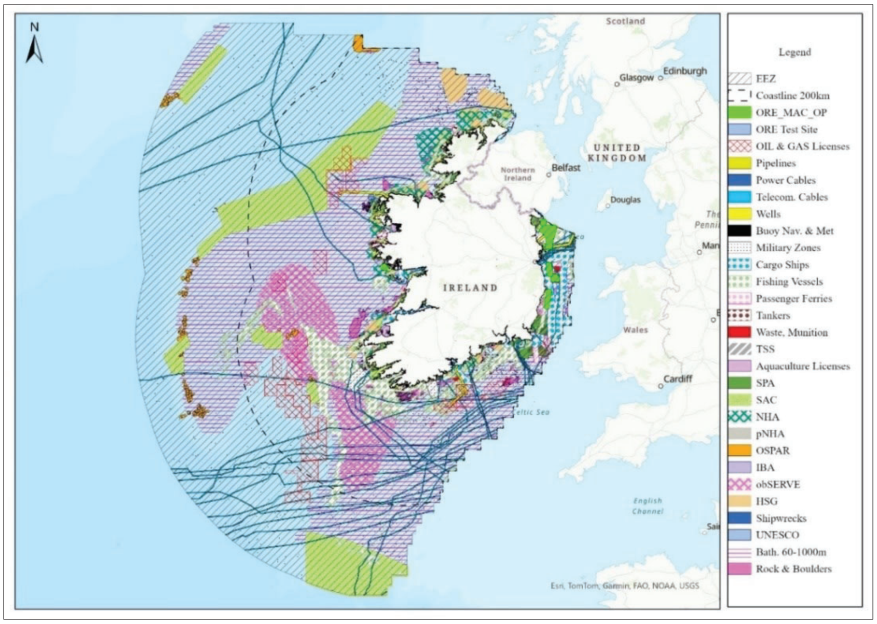

Figure 2: Map presenting considered exclusion areas in Irish waters

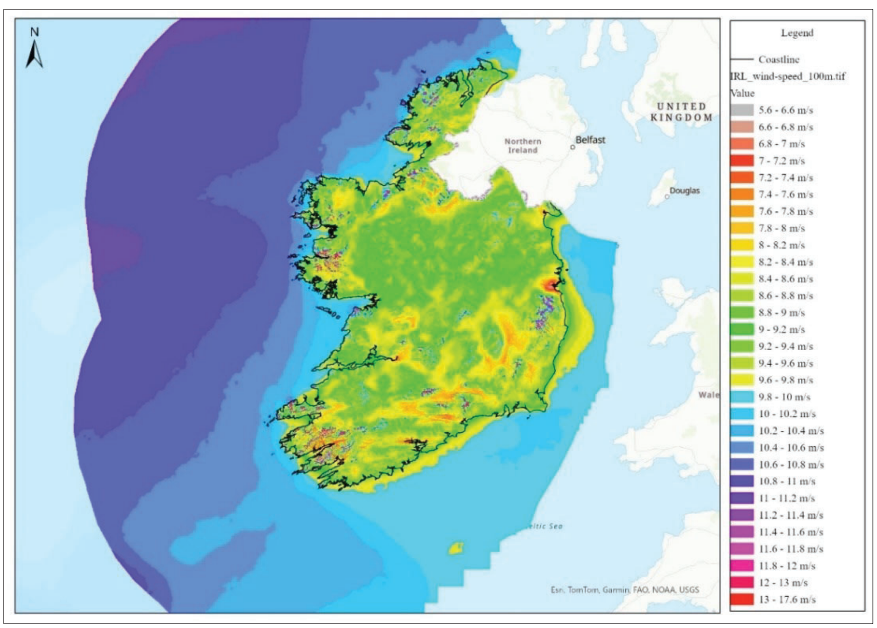

Figure 3: Wind speed distribution across Irish waters and landmass, wind data source: (Global Wind Atlas, 2023)

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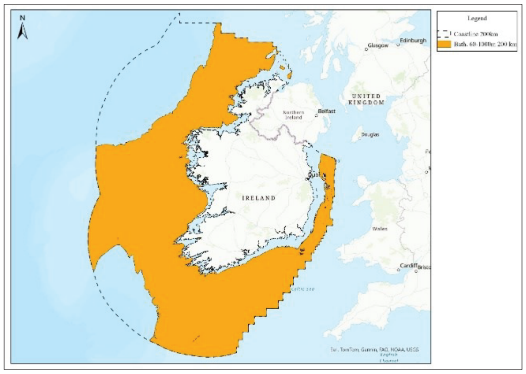

Figure 4: Bathymetry in the range of 60 to 1000 m in the area up to 200 km from the coast

Figure 5: Bathymetry 60-1000 m, exclusion criteria category 1-2

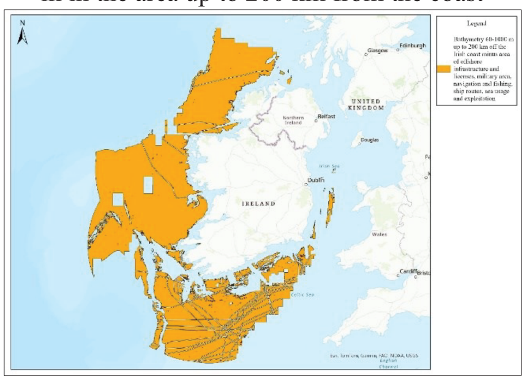

Figure 6: Bathymetry 60-1000 m, exclusion criteria category 1-5

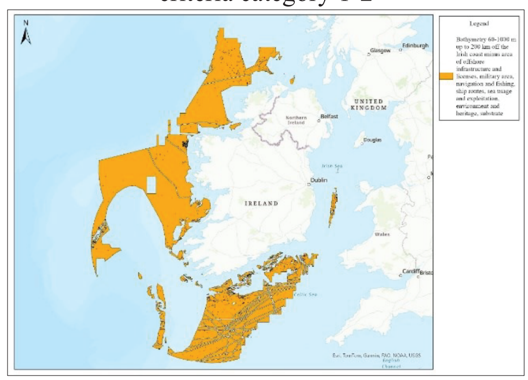

Figure 7: Bathymetry 60-1000 m, exclusion criteria category 1-8

2.1 Installed capacity and energy yield

The EEZ area has been reduced from 427,039 km^2 to 154,814 km^2 by limiting the broad area of interest to a 200 km distance from the shore. In subsequent steps of the exclusion's application, categories one to eight as listed in Table 1, the area of interest suitable for FOWF deployment has been reduced to 78,116 km^2, over one-fifth of the initial area of EEZ.

2.2 Assumptions for estimation of installed capacity

Currently operating FOWF consisting of the following WTG: Siemens SWT 6.0-154 – Hywind Scotland, Siemens Gamesa SG 8.0-167 – Hywind Tampen, Vestas V164-9.5MW – Kincardine and Vestas V164-8.4MW – Wind Float Atlantic. For the estimation of the potential installed capacity in the area of interest, the following assumptions have been made:

1- Exemplary WTG - The DTU 10-MW Reference Wind Turbine (Bak et al., 2013). The proposed WTG is larger than the currently operating offshore WTG but smaller than currently offered the biggest offshore WTGs, which have not been in operation yet. The technical specification of the chosen WTG reflects the present technical possibilities. Table 2 presents the general technical specification of the DTU 10-MW WTG.

Table 2: DTU 10-MW, general technical specification

Technical parameter	Value
Rated power	10.07 MW
Rotor diameter	178.3 m
Hub height (HH)	119 m
Cut-in wind speed	4 m/s
Cut-out wind speed	25 m/s
Rated power wind speed	11.4 m/s

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2- A conceptual array of 100 WTGs laid out in a 10-by-10 grid with a total capacity of 1.07 GW has been chosen as the reference site layout unit. The power density defined as the power capacity of the WTG per square kilometre in the European offshore wind farms is in the range between 3 MW/km^2 to 9 MW/km^2 with a mean power density of 6.1 MW/km^2 (Beiter et al., 2016; Enevoldsen & Jacobson, 2021). Two WTG spacing scenarios have been considered in this study. In the first scenario, WTGs are spaced by 8 Rotor Diameters (RD) and in the second scenario, the WTG array in the dominating wind direction is spaced 10xRD and 8xRD in the crosswind. The installed power density of the first scenario is 5.3 MW/km^2 whereas in the second scenario is 4.2 MW/km^2. Statistics of power density in European waters are based on fixed-bottom offshore wind farms.

2.3 Total installed capacity in the Area of Interest

The resultant area of interest covers 78,116 km^2 and can accommodate a power of 410 GW of WTG, DTU 10-MW, distributed by 8xRD and 328 GW of WTG spaced 10xRD in dominating wind direction and 8xRD in the crosswind. Considering that the area of interest covers only 18.3% of the EEZ, this result proves the enormous potential of Irish waters to accommodate large wind power capacity. As a reference point, it is worth noting, that in 2022 the total installed capacity of the conventional power plants in Ireland was 7.4 GW and 5.1 GW in all Renewable Energy Sources (RES) (EirGrid, 2022).

2.4 Potential annual energy yield and capacity factor

Based on the extent of the area of interest, an estimate of the total installed power capacity has been made. The next step is to assess the theoretical range of an annual energy yield and WTG efficiency. To present efficiency two related coefficients have been proposed. One is the Capacity Factor (CF) and the second is the Full Load Equivalent (FLE). The FLE is a theoretical number of hours in the year when a WTG operates at rated power. The CF is defined as a theoretical percentage of time in the year of operating at rated power. The results are presented as annual gross energy output per one free-standing WTG of DTU 10-MW, RD 178.3 m HH 119 m, meaning that no wake and technical losses have been considered at this stage. Calculations are based on long-term wind statistics at the WTG's hub height of 119 m (Global Wind Atlas, 2023). The gross free-standing WTG energy output in the area of interest is in the range of 53 to 60 GWh/year. The CF in the area of interest varies between 56.7% to 64.1%, whereas FLE respectively is between 4963 h to 5616 h. Figure 8 presents the gross annual energy yield distribution in the area of interest.

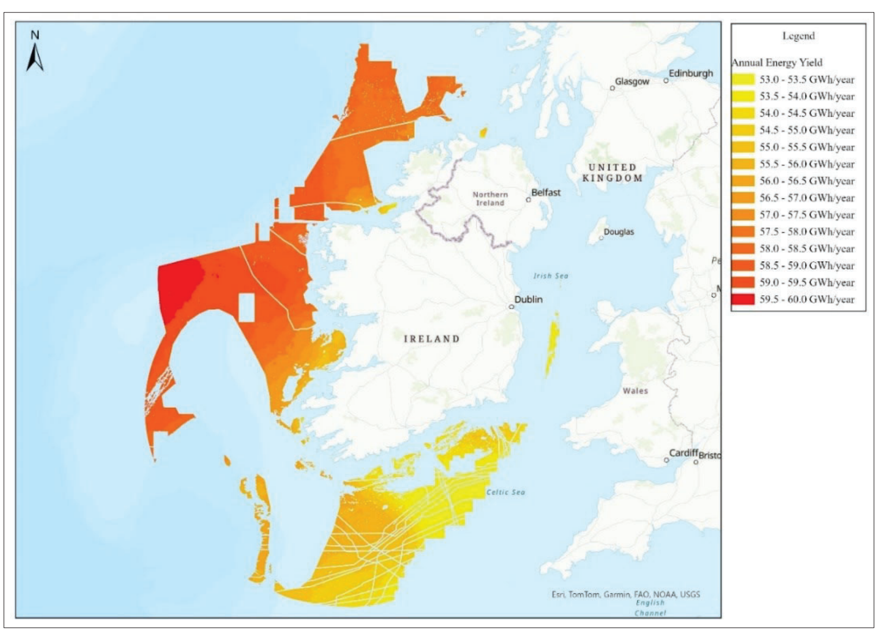

Figure 8: Gross annual energy yield per WTG, DTU 10-MW, RD=178.3 m, HH =119 m

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3 CONCLUSION

The study delved into the potential for deploying floating offshore wind farms, with a specific focus on the Irish exclusive economic zone. It involved an in-depth literature review and analysis of emerging legislation in the offshore renewable energy sector to establish a comprehensive framework. Throughout the research process, the areas of unfavourable characteristics and potential conflicting usage were systematically excluded. This methodology is intended to be applied in the first step of site selection and characterisation and is equally applicable to other offshore renewable energy technologies. A total of 34 exclusion criteria, categorized into eight groups, were identified and utilized. Additionally, certain exclusion areas were expanded by the buffer zone to align with legal requirements, industry guidelines or safety considerations. Despite a significant reduction in the initial broad area of interest, the remaining 18.3% retains substantial potential, with the capacity to accommodate either 328 GW or 410 GW of installed capacity, contingent upon the layout scenario. Furthermore, this is from 26 to 33 times more than the total capacity of all conventional energy plants and renewable energy sources operating in Ireland. Notably, owing to its exceptional wind energy resources, Ireland is strategically positioned not only to meet its power demand but also to bolster its economy, build the industry around offshore renewable energy, and emerge as an energy exporter.

3.1 FURTHER INVESTIGATION

The presented method is the first phase of site selection and characterisation, leading to the identification of potential areas for further investigation. The second phase methodology is currently under development and will be used to evaluate criteria and risk and therefore support the final decision process.

NOMENCLATURE

m	meter
m/s	Meter per second
NM	Nautical mile
W	Watt
W/h	Watt per hour
km^2	Square kilometre
CF	Capacity Factor
COP21	Paris Climate Conference
DTU	Technical University of Denmark
ECMWF	European Centre for Medium-Range Weather Forecasts
EEZ	Exclusive Economic Zone
FLE	Full Load Equivalent
FOW	Floating Offshore Wind
FOWF	Floating Offshore Wind Farm
GIS	Geographic Information System
HH	Hub Height
INSPIRE	Infrastructure for Spatial Information in the European Community
NASA	National Aeronautics and Space Administration
ORE	Offshore Renewable Energy
OREDP	Offshore Renewable Energy Development Plan
OREDP II	Second Offshore Renewable Energy Development Plan
RD	Rotor Diameter
RES	Renewable Energy Sources
WTG	Wind Turbine Generator

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