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Examining the Potential for Floating Offshore Wind Farms in Irish Waters to Achieve the 37 GW Offshore Wind Energy Goal by 2050

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Abstract. Significant legislative initiatives and ambitious targets characterise Ireland's transition to offshore renewable energy. Despite ambitious goals, the full potential of Irish waters has not been thoroughly explored. This study evaluates the capacity of Irish waters to host floating offshore wind farms, taking into account recent policy developments and strategic objectives. A comprehensive methodology was developed, incorporating technical, legislative, and industry best practices, which led to identifying an area of interest spanning 58,486 km^2. Bathymetric analysis indicates that approximately 80% of the total power capacity of 197 GW can be deployed in water depths ranging from 60 m to 200 m. This area of interest can accommodate nearly five times the most ambitious target (Target III) and almost twenty times the lowest target (Target I). The area's assessment of wind conditions and energy yield revealed exceptional potential. The gross energy yield per wind turbine ranges from 80.8 GWh/a to 88.6 GWh/a, averaging 84.8 GWh/a.

1. Introduction

Efforts to combat climate change are crucial, but energy diversification and access to affordable energy sources have also become key factors in the transition to renewable energy.

For these initiatives to succeed, legislation and policy must evolve. Like many other EU coastal states, Ireland has started legislative changes supporting the transition to offshore renewable energy (ORE).

In the end of 2022, seven offshore wind projects with a total capacity of approximately 4.5 GW have received maritime area consent [1]. The leading projects utilise fixed-bottom technology while floating offshore wind (FOW) projects are still in the early stages of development.

The latest Irish policy on ORE aims to install 20 GW by 2040 and 37 GW, or 50 GW, in the "stretch wind target" by 2050. The 27 GW out of 37 GW target and 40 GW out of 50 GW target of ORE are allocated to FOW [2,3].

When selecting locations for offshore wind farms, it is vital to consider technical factors, comply with applicable laws and policies, and mitigate potential conflicts with stakeholders and the environment. Adopting a holistic approach can reduce project risks and enhance public perception, leading to expedited project completion and lower costs.

Nonetheless, there is a lack of diligent inventory of Irish waters that would consider a thorough review of legislation and policy and wind resource characteristics, projected energy output and seabed geophysical properties in viable deployment zones. Finally, the actual capacity of Irish waters to host floating offshore wind farms (FOWF) in the context of the ambitious policy remains unknown.

2. State-of-the-Art

The maximum depth viable for installing fixed-bottom offshore wind turbine generators (WTGs) is between 60 m and 80 m [4,5]; however, about 80% of the sites with the best wind resources are located in deeper waters [6]. Locating the wind farms in these areas will increase energy output and efficiency; however, it poses technical and commercial challenges.

Much of the existing literature on site selection for FOWF tends to focus on a specific method, a single aspect of the process, or a limited number of criteria rather than developing a holistic approach that could be adopted in real-world scenarios.

One of the notable examples of site selection for FOWF in Irish waters is a study conducted by Martinez and Iglesias [7]. The main criterion of site feasibility in this study is LCOE. The researchers also considered several factors restricting the search area, such as bathymetry, distance from shore, and some environmental aspects.

Another example of the site selection for FOWF off the Irish coast was conducted by Loughney et al. [8]. This study aims to apply the Multiple Attribute Decision Analysis (MADA) approach to identify the best site for a FOWF. In order to narrow the search area, researchers considered several factors and finally chose the area of Shannon Foynes Bay off the Galway for a detailed study.

The application of the Multi-Criteria Decision Making method (MCDM) for site selection in Irish waters was also investigated by Deveci et al. [9]. In contrast, this study focused on the rank of five of the most advanced fixed-bottom offshore wind projects; therefore, the project locations are known and fixed. The rank criteria include economic indices, chosen technical aspects and some environmental and social factors.

Another notable example is the study conducted by Diaz and Guedes Soares [10]. Researchers first developed the GIS research tool for FOWF site selection based on exclusion criteria and, in further studies [11–13], supplemented this tool with evaluation criteria and application of MCDMs for final site rank.

While there are commendable examples of research related to site selection for FOWFs, there remains an opportunity to enhance the methodology for practical implementation. Many existing studies face challenges, including limited connections to relevant legislation and policies and the need for more clearly defined objectives that align with the utilised criteria. Furthermore, incorporating tools and data sets recognised and widely used in the wind industry would enhance the methodology. Addressing these aspects could significantly improve the applicability of these methods in real-world scenarios and allow for the estimation of the real potential of the waters to host FOWF.

3. Methodology

The methodology is divided into two sections. Firstly, it presents a delineation of an area of interest (AOI) that is feasible for FOWF deployment. Secondly, assumptions are presented to estimate the AOI's power capacity and energy yield.

3.1 Area of interest

The methodology must incorporate the legislative, policy, and technical requirements and employ tools and data recognised in the wind industry. In order to define a set of criteria, a hierarchical decomposition of the main objective into sub-objectives linked to relevant legislation and policy has been proposed. This creates a robust framework and justifies consideration of each criterion's function (exclusion or evaluation).

The main objective is to evaluate the potential of Irish waters within the context of the goals of FOWF development. Eight sub-objectives representing a broad spectrum of development aspects have been proposed to achieve this primary objective. Finally, each sub-objective has been linked to policy and legislation, informing the selection of criteria. As a result, 41 criteria were identified and considered in the study. Data processing and spatial analysis were conducted using GIS software. Consequently, the final exclusion map presenting the AOI has been derived. The sub-objectives and criteria together with the reference to relevant policy and legislation, are presented in Table 1.

Table 1. Exclusion criteria, connection to legislation and policy, buffer zones and sources of data.

Sub-objectives	No.	Criteria	Policy and legislation	Data source
1. Legislative	1.1	EEZ	[14–16]	[17]
	1.2	Maritime Spatial Planning (MSP)	[18–20]	[15,21]
	1.3	OREDP and OREDP II	[15,16]	[15,16,21]
2. Offshore infrastructure and licenses	2.1	Existing and consented ORE	[19]	[22,23]
	2.2	ORE Test sites	[15,20]	[22]
	2.3	Gas and oil platforms and licenses	[15,19]	[22]
	2.4	Underwater pipelines	[15,19,20]	[21,22]
	2.5	Underwater Power Cables and Telecommunication	[15,20]	[22,24–27]
	2.6	Exploration wells	[15,19]	[28]
	2.7	Meteorological equipment, navigation buoy	[15]	[28]
3. Military zones	3.1	Military training zones	[20]	[22]
4. Navigation and fishing, ship routes	4.1	Cargo ships	[19,20]	[22]
	4.2	Passenger ferries		[22]
	4.3	Tankers		[22]
	4.4	Fishing		[22]
	4.5	Other: sailing, dredging, service, tug and tow, pleasure, high-speed craft, military		[22]
5. Sea usage and exploitation	5.1	Waste, sewage, munition, dredge	[15,20]	[22,29]
	5.2	Anchorage area	[20]	[15,30]
	5.3	Traffic Separation Scheme (TSS)	[20]	[15,30]
	5.4	Licensed aquaculture AQ.	[19]	[28]
6. Environment	6.1	Special Protection Areas (SPA)	[15,20,31]	[32]
	6.2	Special Areas of Conservation (SAC)		[32]
	6.3	Proposed and existing Natural Heritage Areas (NHA), (pNHA)		[32]
	6.4	OSPAR Declining Threatened Habitats		[22]
	6.5	Important Bird Areas (IBA)		[33]

Sub-objectives	No.	Criteria	Policy and legislation	Data source
	6.6	ObSERVE High-Density Areas		[15,34]
	6.7	Herring Spawning Grounds (HSG)	[15,20]	[28]
	6.8	Marine Protected Areas (MPAs)	[15,20]	[22]
	6.9	RAMSAR Convention	[15,20]	[22]
7. Heritage and social	7.1	UNESCO World Heritage Sites and Global Geoparks	[15,20]	[35]
	7.2	UNESCO Dublin Bay Biosphere		[36]
	7.3	Shipwrecks	[20]	[22,37]
	7.4	Blue Flag Beaches and Green Coast Beaches	LTA [20]	[22]
	7.5	Seascape and landscape	LTA	[21]
8. Technology	8.1	Bathymetry	[15]	[22]
	8.2	Sea substrate	NR	[22,37]
	8.3	Distance to shore	NR	[28]
	8.4	Wind speed	NR	[6]
	8.5	Seabed slope	NR	[22]
	8.6	Landslide susceptibility	NR	[22]
	8.7	Submarine gas and fluid emissions	NR	[22]

NR- no reference to legislation and policy, LTA- to be considered in Lower Tier Assessment

3.2 Power density, capacity of AOI and forecasted energy yield

The theoretical power density (PD) calculation is defined as capacity per square kilometre, and the estimation of energy yield in the AOI is based on the exemplary WTG IEA-15 MW offshore reference turbine [38].

The average PD of European offshore fixed-bottom wind farms is 6.1 MW/km^2 [4,39]. The PD of existing FOWF, Hywind Scotland, Hywind Tampen and Kincardine is 9.8 MW/km^2, 8.6 MW/km^2, and 12.5 MW/km^2, respectively. Due to the small-scale and pilot nature of existing FOWFs, the PD of these wind farms may not correlate with the PD of future large-scale FOWFs; therefore, it should be considered only as indicative.

In the latest Leasing Round 5 for Celtic Sea FOW conducted by Crown Estate the minimum allowed PD of FOWFs in the proposal is 4 MW/km^2 [40]. Assuming that the lowest commercially acceptable PD is 4 MW/km^{2,} the proposed wind farm layout has been adjusted to meet this requirement. A 10-by-10 grid of WTGs, with a total capacity of 1.5 GW, has been used as a reference site layout. In order to achieve the required minimum power density, the spacing between WTGs was set to 8.8 RD. The layout assumptions are presented in Figure 1.

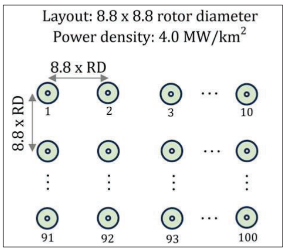


Figure 1. Layout assumption adopted in the study.

The energy yield estimation is based on the power curve of the IEA-15 MW wind turbine and the Weibull distribution of the ten-year (2008 to 2017) average annual wind speed at hub height (HH). The long-term wind data with a spatial resolution of 250 m x 250 m has been obtained from the Global Wind Atlas [6], and the vertical extrapolation to HH has been performed using the WAsP model [41].

4. Results and discussion

This section is organised into several subsections that present results obtained from executing the various steps of the methodology.

4.1 Area of interest

The resultant AOI covers 58,486 km^2, 13.7% of the initially investigated area of the Irish EEZ. The final AOI is a product of applying pertinent exclusion criteria, as detailed in Table 1. Figure 2 presents the AOI highlighting suitable locations for deploying FOWF within the case study area in chosen bathymetric ranges and visible seas' boundaries.

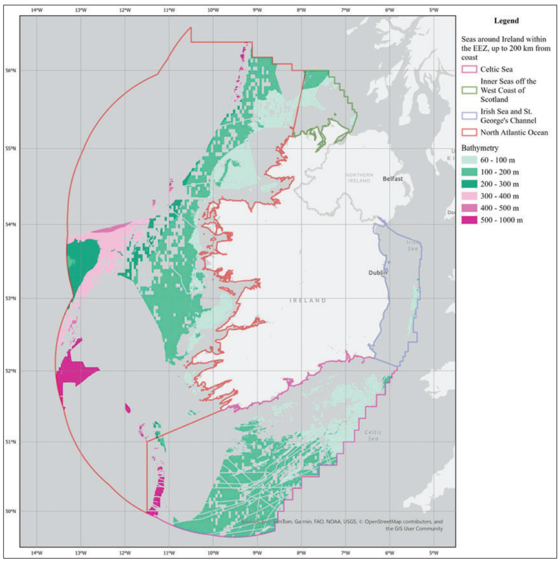


Figure 2. The final extent of the AOI, considering chosen bathymetry ranges and the boundaries of seas around Ireland, defined within the EEZ, a distance of 200 km from shore and constrained by relevant exclusion criteria.

The spatial coverage of the AOI within a particular sea is summarised in Table 2.

Table 2. The spatial coverage of the AOI within a specific sea, along with the percentage of that coverage relative to the total AOI and the total sea surface area.

Area	Area of interest [km^2]	Percentage of the AOI in a specific sea compared to the total AOI	Percentage of the AOI in a specific sea compared to the total sea surface area
AOI- All seas	58,486	100.0%	13.7%

Area	Area of interest [km²]	Percentage of the AOI in a specific sea compared to the total AOI	Percentage of the AOI in a specific sea compared to the total sea surface area
AOI- Atlantic Ocean	35,453	60.6%	10.8%
AOI- Inner Seas off the West Coast of Scotland	1,515	2.6%	26.8%
AOI- Irish Sea	395	0.7%	3.8%
AOI- Celtic Sea	21,124	36.1%	25.7%

The Atlantic Ocean comprises 60.6% of the AOI, while the Celtic Sea encompasses 36.1%. The Inner Seas off the West Coast of Scotland account for 2.6%, and only 0.7% is in the Irish Sea. The most notable reduction in available space occurs in the Irish Sea, where a mere 3.8% of the sea area within the Irish EEZ is suitable for FOWF deployment.

The bathymetric analysis indicates that 25.7% of the AOI is located at 60 m to 100 m depths, while 53.6% resides within 100 m to 200 m depths. Therefore, nearly 80% of the potential power capacity can be installed in waters up to 200 m deep.

4.2 Wind conditions and energy yield in the AOI

The long-term annual mean wind speed at a height of 100 m within the AOI ranges from 9.7 m/s to 11.0 m/s, with an average of 10.2 m/s and a median of 10.1 m/s. The highest mean wind speed, recorded at 10.4 m/s, occurs in the Atlantic Ocean, while the lowest, at 9.9 m/s, is observed in the Irish Sea. Wind speed distribution in the AOI with marked seas' boundaries in the study area is presented in Figure 3.

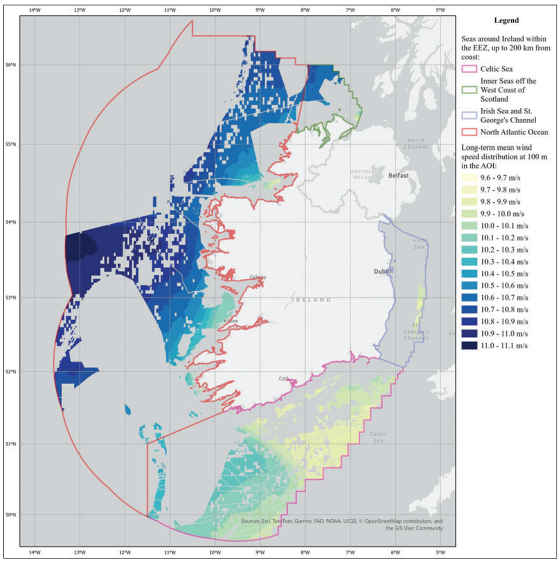


Figure 3. Long-term annual wind speed distribution in the AOI at 100 m and the boundaries of seas around Ireland, within the EEZ and 200 km distance from the coast. Based on wind data obtained from Global Wind Atlas covering the period 2008 to 2017 [6].

The region with the most abundant wind resources is located in the western part of the Atlantic Ocean, specifically between latitudes 53°N and 54°N, extending westward from longitude 13°W. In this area, the long-term mean annual wind speed at a height of 100 m reaches 11 m/s. Additionally, excellent wind conditions can be found in the Inner Seas off the West Coast of Scotland, where the mean wind speed is 10.3 m/s, with a median of 10.1 m/s, a maximum of 10.7 m/s, and a minimum of 9.9 m/s. The Celtic Sea exhibits slightly milder wind conditions compared to the Atlantic Ocean and the Inner Seas off the West Coast of Scotland.

The annual energy yield forecast has been based on long-term annual wind distribution across AOI. Results illustrate the forecasted annual gross energy yield per WTG. A summary of the energy yield characteristics in the AOI and in specific sea regions is presented in Table 3.

Table 3. Forecasted energy yield per WTG in the AOI and in specific sea regions.

Parameter	AOI All	AOI - Atlantic Ocean AOI	AOI - Inner Seas off the West Coast of Scotland	AOI - Irish Sea	AOI - Celtic Sea
AEP Mean [GWh/a]	84.8	86.2	85.7	81.5	82.8
AEP Min. [GWh/a]	80.8	82.3	83.2	80.9	80.8
AEP Max. [GWh/a]	88.6	88.6	86.6	83.7	84.8
AEP Median [GWh/a]	84.9	86.3	85.8	81.4	82.8
CF Mean	64.5%	65.6%	65.2%	62.1%	63.0%
CF Min.	61.5%	62.6%	63.3%	61.6%	61.5%
CF Max.	67.4%	67.4%	65.9%	63.7%	64.6%
CF Median	64.6%	65.7%	65.3%	62.0%	63.1%

The energy yield within the AOI ranges from 80.8 GWh/a to 88.6 GWh/a, with an average of 84.8 GWh/a. The highest mean energy yield is anticipated in the AOI of the Atlantic Ocean, reaching 86.2 GWh/a, while the lowest mean output is found in the Irish Sea at 81.5 GWh/a. Significant energy yields are also projected for the Inner Seas off the West Coast of Scotland and the Celtic Sea, averaging 85.7 GWh/a and 82.8 GWh/a, respectively. Although the Irish Sea has the lowest forecasted energy yield, it still holds considerable potential, with a mean capacity factor (CF) of 62.1%.

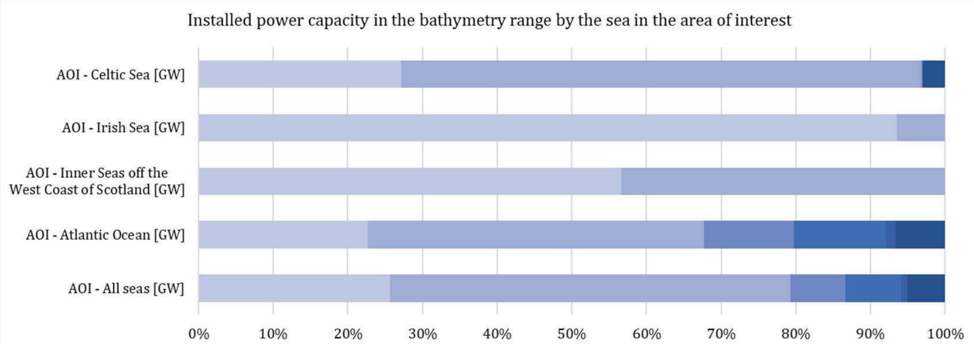
4.3 Potential of AOI, total installed power capacity

The AOI can host over 13,000 IEA-15 MW reference WTGs, totalling an impressive power capacity of 197 GW. The potential total installed capacity in a particular sea is presented in Table 4.

Table 4. The potential of the installed power capacity by the sea and the share of specific sea regions in the total capacity.

AOI within the sea	Installed power capacity [GW]	Percentage of installed capacity
AOI- All seas	196.6	100.0%
AOI - Atlantic Ocean	119.2	60.6%
AOI - Inner Seas off the West Coast of Scotland	5.1	2.6%
AOI - Irish Sea	1.3	0.7%
AOI - Celtic Sea	71.0	36.1%

The largest FOWF can be situated in the Atlantic Ocean and the Celtic Sea. The Irish Sea and the Inner Seas off the West Coast of Scotland can only support 3.3% of the overall installed capacity. The power capacity in chosen bathymetric ranges has been presented in Figure 4.



	AOI - All seas [GW]	AOI - Atlantic Ocean [GW]	AOI - Inner Seas off the West Coast of Scotland [GW]	AOI - Irish Sea [GW]	AOI - Celtic Sea [GW]
60 - 100 m	50.5	27.1	2.9	1.2	19.3
100 - 200 m	105.3	53.6	2.2	0.1	49.5
200 - 300 m	14.5	14.3	0.0	0.0	0.1
300 - 400 m	14.7	14.7	0.0	0.0	0.0
400 - 500 m	1.6	1.6	0.0	0.0	0.0
500 - 1000 m	10.0	7.9	0.0	0.0	2.1

Figure 4. Installed power capacity in bathymetry range by the sea in the AOI.

The bathymetric assessment shows that 50.5 GW of installed power capacity can be deployed in water depths ranging from 60 m to 100 m, while waters with a bathymetry range between 100 m and 200 m can accommodate 105.3 GW. However, regions with deeper waters, specifically those between 200 m and 1000 m, can only support 40.8 GW of installed power capacity.

The ambitious plans project the deployment of 20 GW of ORE by 2040, primarily to meet domestic demand, with more ambitious forecasts estimating 37 GW or even 50 GW by 2050. Approximately 10 GW out of the 20 GW target, 27 GW out of the 37 GW target, and 40 GW out of the 50 GW target will be achieved through the deployment of FOWF [2,3]. The highest targets anticipate significant energy exports to the UK and the EU.

The potential installed power capacity across the entire AOI and within specific marine regions and their bathymetry are detailed in Table 5.

Table 5. The potential of the installed power capacity by the sea and the specific bathymetry for three considered targets.

Targets	Bathymetry in AOI	AOI - All seas	AOI - Atlantic Ocean	AOI - Inner Seas off the West Coast of Scotland	AOI - Irish Sea	AOI - Celtic Sea
I - 10 GW	60 - 1000 m	1966%	1192%	51%	13%	710%
	60 - 100 m	505%	271%	29%	12%	193%
	100 - 200 m	1053%	536%	22%	1%	495%
	200 - 300 m	145%	143%	0%	0%	1%
	300 - 400 m	147%	147%	0%	0%	0%
	400 - 500 m	16%	16%	0%	0%	0%
	500 - 1000 m	100%	79%	0%	0%	21%
II - 27 GW	60 - 1000 m	728%	441%	19%	5%	263%
	60 - 100 m	187%	100%	11%	5%	71%
	100 - 200 m	390%	198%	8%	0%	183%
	200 - 300 m	54%	53%	0%	0%	0%
	300 - 400 m	54%	54%	0%	0%	0%
	400 - 500 m	6%	6%	0%	0%	0%
	500 - 1000 m	37%	29%	0%	0%	8%
III - 40 GW	60 - 1000 m	492%	298%	13%	3%	178%
	60 - 100 m	126%	68%	7%	3%	48%
	100 - 200 m	263%	134%	6%	0%	124%
	200 - 300 m	36%	36%	0%	0%	0%
	300 - 400 m	37%	37%	0%	0%	0%
	400 - 500 m	4%	4%	0%	0%	0%
	500 - 1000 m	25%	20%	0%	0%	5%

The AOI has the capacity to accommodate nearly five times the most ambitious target (Target III) and almost twenty times the lowest target (Target I). Targets I and II can be realised by deploying FOWF within the Atlantic Ocean at depths ranging from 60 m to 100 m. By extending operations to depths of up to 200 m, all three targets can be successfully attained within these waters. In the Celtic Sea, Target I is achievable within the 60 m to 100 m bathymetric range; however, by expanding the operational depth to 200 m, all three targets can also be met. Furthermore, there is considerable potential in the Inner Seas off the West Coast of Scotland, where approximately half of Target I can be realised through deployment in bathymetry ranging from 60 m to 200 m. In contrast, the Irish Sea offers the least potential for installed power capacity, with only 3.3% to 13.3% of the respective targets being attainable; nonetheless, nearly all deployments can occur at depths between 60 m and 100 m.

5. Conclusions

This study addresses the research question regarding the realistic potential of Irish waters to accommodate FOWFs, considering recent policy developments and the country's strategic ambitions.

The findings reveal that the AOI constitutes 13.7% of the Irish EEZ. Notably, approximately 60% of the AOI is situated in the Atlantic Ocean, while the AOI in the Irish Sea accounts for only 0.7% of the total area. Approximately 80% of the AOI lies in relatively shallow waters with a bathymetry range of 60 m to 200 m.

The primary factors contributing to the reduction in the available area include bathymetry, distance from the coast, environmental constraints, shipping routes, and fishing activities.

The annual average wind speed in AOI exceeds 7 m/s at a height of 100 m, which is considered the minimum required annual average wind speed to ensure the project's financial viability [4,15].

The gross annual energy yield in this area ranges from 80.9 GWh/a to 88.6 GWh/a, with a mean value of 84.8 GWh/a. This translates to a mean CF of 64.5%, with minimum and maximum values of 61.5% and 67.4%, respectively. For context, the world's top-performing FOWF, Hywind Scotland, achieved a CF of 54% over five years of operation [42]. The average CF for offshore wind farms in the UK is approximately 40% [43].

The AOI can sustain a significant number of WTGs, amounting to a total installed power capacity of 197 GW, more than 16 times the total installed power capacity of all conventional and renewable energy sources operating in Ireland in 2022 [44]. The Atlantic Ocean can support up to 119.2 GW of installed power capacity, while the Celtic Sea has the potential for 71 GW. In contrast, the Irish Sea and the Inner Seas off the West Coast of Scotland can each accommodate 1.3 GW and 5.1 GW, respectively.

The most ambitious target of deploying 40 GW of FOWFs can be met by utilising relatively shallow waters with a bathymetry of 60 m to 100 m.

In the context of surplus energy export, the most favourable AOI appears to be located in the Inner Seas off the West Coast of Scotland. This region benefits from exceptional wind conditions, advantageous bathymetry, and proximity to Northern Ireland and Scotland. The Celtic Sea also holds significant potential for energy export, particularly with the possibility of interconnections to the UK and France. Additionally, the AOI in the Irish Sea is valuable from a commercial perspective due to its closeness to the high-energy demand area of Dublin, along with its favourable bathymetry. The AOI of the Atlantic Ocean offers the most significant potential because of its vast area and highest energy yield. Nonetheless, risks related to challenging sea conditions may not compensate for energy gain. Given the considerable distance to neighbouring countries, FOWF in this area is anticipated to primarily cater to domestic demand, with any surplus energy being exported through interconnections and green hydrogen initiatives.

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