Data driven wet-storage solutions for floating offshore wind in Ireland

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Abstract. Floating Offshore Wind (FOW) generation in Ireland could deliver up to 37 gigawatts of energy by 2050. A critical enabler for this will be wet storage, the temporary nearshore storage of FOW units in suitable areas prior to installation. Wet storage is expected to be particularly imperative in Ireland due to the harsh wave climate, resulting in narrower installation weather windows, off the Irish coast. This study is addressing the major unknowns surrounding wet storage, focusing on the technical challenges and identification of potential sites. The sites analysis was performed using advanced GIS software considering a range of geospatial criteria representing the various constraints restrictions and opportunities at play. A validation of the wave data used has been performed to assess accuracy. Furthermore, wave and tidal model downscaling has also been performed in order to adequately represent the oceanographic conditions inside some of the more enclosed areas/ports in the study area. Validation results have indicated generally good agreement between modelled and in-situ wave data, despite the tendency for the model to underestimate extreme values (i.e. during storm events). The results of the site suitability analysis reveal extensive areas of potential for wet storage within the Shannon Estuary and Bantry Bay on the southwest coast in addition to some limited potential at Belfast Lough in the north.

1. Introduction

With 34% of the Ireland's total electricity generation coming from wind as of 2022, the nation is estimated as having the second highest share of wind-generated electricity in Europe, trailing only to Denmark, where wind energy constitutes around 54% of the electricity supply [1]. In contrast to the United Kingdom, a leader in the offshore wind sector, Ireland currently operates just one offshore wind facility, the Arklow Bank Wind Park Phase 1. There has been a renewed focus on expanding fixed-bottom offshore wind projects in the shallower Irish Sea and Celtic Sea of late (off the east and south coasts respectively).

It is off Ireland's west coast in the deeper Atlantic waters however that represents one of Europe's most significant renewable energy opportunities. With a maritime area more than seven times the size of its landmass extending far offshore into the Atlantic Ocean, it is estimated that Floating Offshore Wind (FOW) technology deployed in Irish waters could yield up to 37 gigawatts of energy by 2050, six times more than the current domestic electricity demand [2].

Despite this promise, the development of FOW farms in Ireland faces critical challenges, particularly related to port infrastructure [3]. A lack of sufficient resources allocated to address these infrastructural needs may compel Ireland to depend on UK or EU ports for project delivery, leading to lost opportunities for local job creation, potential delays in project delivery and increased costs. To meet the anticipated pace of deployment, it is essential for Ireland to develop ports capable of supporting this emerging market. A vital aspect of this port infrastructure for delivering FOW will be wet storage facilities, particularly necessary in Ireland due to the harsh wave climate off the west coast restricting deployment weather windows. It is required as a buffer area to temporarily store fabricated units that have either been manufactured nearby or delivered from further afield, prior to being integrated and towed to site. This temporary storage of Floating Offshore Wind Turbines (FOWTs) in the marshalling and assembly port will ensure that the assets can be deployed swiftly when a suitable weather window arrives. Wet storage will also be required for the semi-submersible foundations (pre-integration), but this study only focuses on the scenario of wet storage for fully integrated units (post-integration) which warrants consideration of more restrictive criteria. By addressing logistical challenges such as these at an early stage, Ireland can focus on developing port areas with the right geographical attributes to unlock its vast Atlantic offshore wind potential and significantly enhance its contribution to renewable energy generation in Europe.

2. Study Assumptions

The study area encompasses all regions within Ireland's territorial waters, including those of Northern Ireland. This broad scope incorporates areas of the Irish Sea, the Inner Seas off the West Coast of Scotland (ISWCS), the Celtic Sea, and the Atlantic Ocean. Key ports within the study area include Shannon Foynes Port, the Port of Cork (encompassing Bantry Bay and Cork Harbour), the Port of Waterford, Rosslare Europort, Dublin Port, Belfast Harbour, the Port of Larne, Foyle Port, Killybegs Harbour, and the Port of Galway.

In Table 1, the key assumptions underpinning this study are delineated. Notably, due to the current absence of any operational large-scale commercial FOW farms worldwide, the assumptions presented are not derived from empirical data but are grounded in the informed perspectives of industry and academic experts. These insights reflect the anticipated advancements and emerging trends within the sector, thus ensuring their relevance to the evolving landscape of FOW technology.

3. Data and Methodology

The met-ocean data used in this study is described in detail below. As the wave climate was one of the most influential and stochastic input variables to this analysis, a validation was performed against data from an in-situ source within the study area. The wind data was not influencing the results (as the chosen limits were not exceeded) and a reliable in-situ source of current speed data was not found, so these met-ocean variables were not validated in this study. An extension of both the wave model and tidal model into enclosed areas of the study region is also detailed in this section. Sources for other data such as that of a geophysical, infrastructural and societal nature are also documented here.

Table 1. Main technical and geographical study assumptions.

Parameter	Value
Foundation size	L: 85-125m, W: 75-120m, H: 35-50m
Turbine size	RD=270m, Hub height=165m, Max. tip height=300m
Foundation draft	12m
Quantity in wet storage	5-10 units
Deployment window	April to October
Mooring system	Catenary or semi-taut
Max Hs for wet storage	2m 50 year return Hs
Max current speed for wet storage	2m/s at max spring tide peak U
Max wind speed for wet storage	30m/s 50 year wind speed (sustained)
Minimum depth for wet storage	13m LAT
Desired seabed character	≠ to 'Rock or other substrata' (Folk-5 classification)
Minimum wet storage area required	725 ha

3.1 Wave climate

A 20-year historical dataset of significant wave height for the study area was necessary for this analysis. This type of data is readily accessible through the Copernicus Marine Service website [4]. The specific product used, titled 'Atlantic - Iberian Biscay Irish - Ocean Wave Reanalysis' (A-IBI-OWR), spans a geographical range of 19°W to 5°W and 56°N to 26°N [5], fully encompassing the study area. This product was selected primarily due to its good temporal resolution, providing data on an hourly basis. Additional details about the product are outlined in Table 2. Utilizing this dataset, the 50-year return period for significant wave height was computed in Python with the assistance of the pyextremes library [6].

3.2 Wind climate

Hourly wind data was obtained from the Copernicus ERA5 database [7], a reliable source for met-ocean products. As with the wave data, this wind data was downloaded in the form of netCDF files. Further details about the dataset, including its spatial and temporal scope, are summarized in Table 3. To estimate the 50-year return period for wind speed, the data was again processed and analysed using Python, with the help of the pyextremes library [6].

Table 2. Wave model details.

Parameter	Description
Name	Atlantic - Iberian Biscay Irish - Ocean Wave Reanalysis
Spatial Resolution	0.05° x 0.05°
Temporal Resolution	Hourly
Analysis Period	2000 – 2019 (20 years of data)
Underlying model	MFWAM (Meteo-France)
Variables selected	Spectral significant wave height (Hm0)

Table 3. Wind model details.

Parameter	Description
Name	ECMWF Reanalysis v5 (ERA5)
Spatial Resolution	0.25° x 0.25°
Temporal Resolution	Hourly
Analysis Period	2000 – 2019 (20 years of data)
Variables selected	10m u-component of neutral wind, 10m v-component of wind
Data used in calculations	Root mean square of the u and v components of the 10m wind speed

Table 4. Tidal model details.

Parameter	Description
Name	ROMS hydrodynamic model (Regional Ocean Modelling System)
Spatial Resolution	1.9 km * 1.9 km
Temporal Resolution	Hourly
Analysis Period	2020-01-01 to 2020-12-30 (1 year of data)
Underlying model/equation	Reynolds-averaged Navier–Stokes equations
Variables selected	'uB' (U-component barotropic velocity) and 'vB' (V-component barotropic velocity)

3.3 Tidal climate

The ocean current data utilized in this study was sourced from the Marine Institute [8]. Their ROMS (Regional Ocean Modelling System) hydrodynamic model encompasses the entire study area, providing comprehensive coverage. Details about the dataset, including its specifications and parameters, are outlined in Table 4. Once downloaded, the data was processed in MATLAB to calculate and visualize the maximum peak current velocity.

3.4 Validation

As the wave data was identified to be the most influential criteria to the site suitability analysis (along with water depth), a validation of the model applied was performed using in-situ data obtained from a wave buoy located within the study area. The WestWave Buoy is situated northwest of the Shannon Estuary 5km from the coast of Co. Clare. A one-year time series of hourly significant wave height (Hs) data from this buoy was downloaded from the Irish Marine Institute's Wave Buoy Observations site [9]. The in-situ data was compared against the grid of model data closest to the coordinates of each validation site using a co-location script in MATLAB. Only the data closest in time to each other, and no more than 30 minutes apart, was selected for the comparison. The bias (Equation 1), root mean square error (RMSE; Equation 2), scatter index (SI; Equation 3) and correlation coefficient (R; Equation 4) were then calculated.

$$Bias = \frac{1}{N}\sum_{i=1}^{N} e_i \tag{1}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N} {e_i}^2} \tag{2}$$

$$SI = \frac{RMSE}{U} \tag{3}$$

$$R = \frac{1}{\sigma_U \sigma_u (N-1)}\sum_{i=1}^{N}(U_i - U)(u_i - u) \tag{4}$$

Where *e* represents the error/residual, *i* is an index that represents the individual observation in the dataset, *U* and *u* denote the mean of the *in-situ* and modelled significant wave height respectively, σ_U and σ_u their standard deviations, and *N* the number of match up samples/data pairs considered.

3.5 Geophysical data
Bathymetry data for the study area was primarily sourced from INFOMAR [10], offering ~10m spatial resolution coverage of Irish waters collected via multibeam echosounder (MBES) technology, with gaps in areas like Northern Ireland filled by the EMODnet Digital Terrain Model [11] at ~115m spatial resolution, integrating survey data, composite DTMs, and GEBCO Digital Bathymetry. The datasets were merged in ArcGIS Pro, prioritizing INFOMAR's higher resolution. Seabed substrate data, largely from INFOMAR [10] and provided via EMODnet [11], was classified using the Folk-5 grain size system, though gaps remain in areas like Northern Ireland and parts of the west coast.

3.6 Other data
Data representing other hard constraints to the identification of appropriate areas for wet storage of FOWTs included aquaculture sites, vessel movement, restricted areas, cable and pipeline infrastructure. Aquaculture sites were downloaded from the Department of Agriculture Food and the Marine for Republic of Ireland [12] and from the Department of Agriculture, Environment and Rural Affairs for Northern Ireland [13]. Shipping channels were digitised using Admiralty chart data [14] and AIS density data [15]. Anchorage areas, restricted areas and subsea cable and pipeline infrastructure were also digitised from the Admiralty chart data.

3.7 Oceanographic model extension
Although the spatial resolution of the chosen wave product (Table 2) and current speed model (Table 4) was acceptable for replicating conditions in the majority of the study area, an extension was required into some of the enclosed areas of interest around the coast using a procedure commonly referred to as downscaling. Using the pre-processed wave data, current speed data and the INFOMAR bathymetry data as inputs, DHI's MIKE-21Coastal and Marine Modelling software was applied for the Shannon Estuary and Cork Harbour to replicate the oceanographic conditions within these enclosed areas at a mesh resolution of approx. 100m. Downscaling of the wind model was not required or performed as the local geospatial variability is far less pronounced in comparison to the oceanographic variables.

3.8 Multi-Criteria Decision Analysis
With all of the necessary data gathered, processed and, in the case of the wave data, validated, the multi-criteria decision analysis model was developed in ArcGIS Pro to which this data was fed. The model uses a procedure referred to as sieve mapping, whereby each data variable is assessed for a decision on which geographic areas meet the desired criteria to continue to the next stage of assessment, and which geographic areas do not meet the criteria to be scrapped for no further consideration (Figure 1).

4. Results

4.1 Validation
The results of validating the wave model show good overall agreement between the modelled and in-situ Hs values, with a mean bias of -0.35m, RMSE of 0.47, SI of 0.21 and R coefficient of 0.98 (Table 5). Figure 2 (left) shows the comparison of Hs values produced by the model in comparison to the in-situ source throughout the one-year time-series selected for the validation. Underestimations are apparent for extreme values (peaks) during some storm events. Despite this, the scatter plot diagram in Figure 2 (right) and the results in Table 5 confirms generally good agreement between modelled and in-situ values.

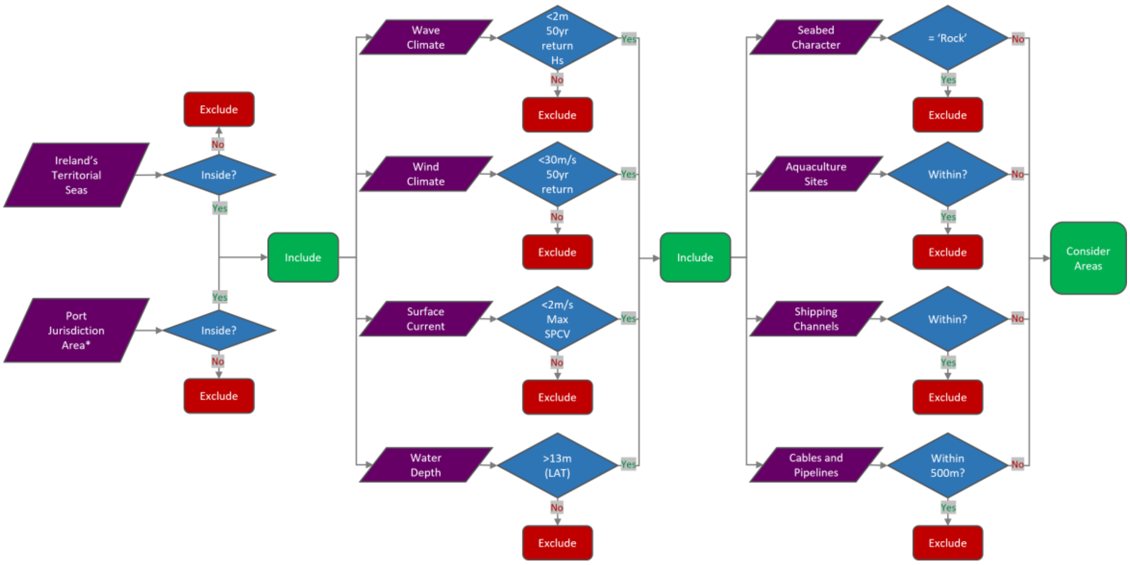

Figure 1. MCDA methodology flow diagram.

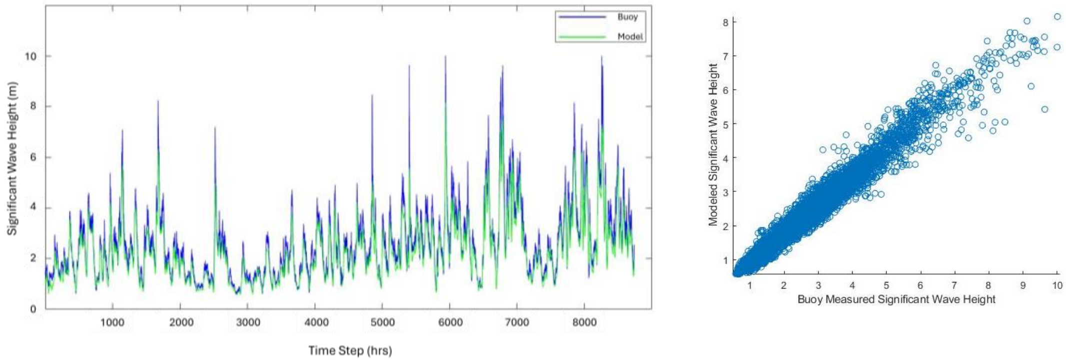

Figure 2. Validation results: time series comparison (left) and scatter plot diagram (right).

Table 5. Validation results: parameters.

Bias	RMSE	SI	*R*
0.3459	0.4773	0.2126	0.9807

4.2 Oceanographic model extensions

An example of extending the oceanographic models into the enclosed areas using the downscaling procedure in Mike-21 is shown in Figure 3 for the mouth of the Shannon Estuary. This is an area where the underlying wave model began to fail at accurately representing the wave climate (Figure 3a). The result of the downscaling produces a more realistic representation of the wave climate inside the estuary with the effects of coastal sheltering clearly evident behind the headlands and islands, where lower 50-year Hs values are evident (Figure 3b). The current speed model did not extend into the estuary whatsoever (Figure 3c), further warranting the necessity for downscaling of this parameter here, the results of which show the strongest max peak current velocity values around headlands, islands and through narrow channels, as expected (Figure 3d).

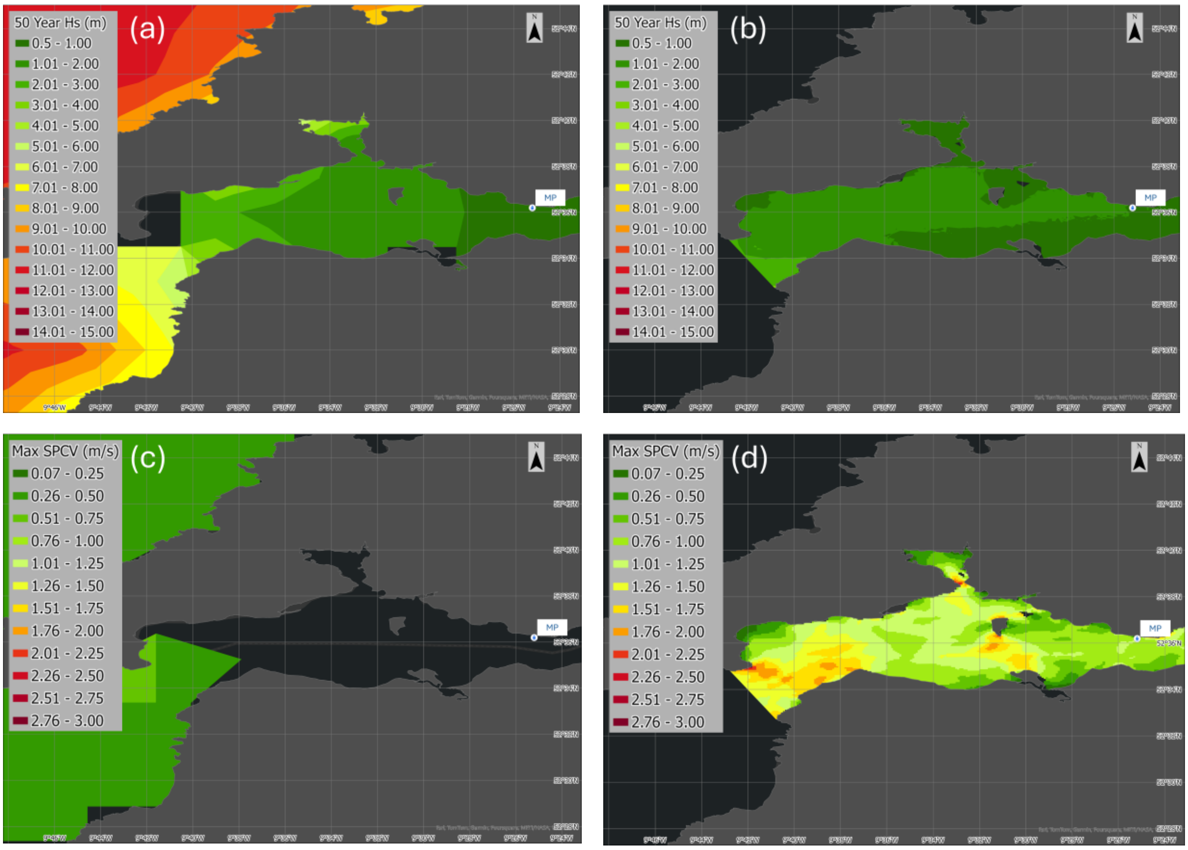

Figure 3. Results of the oceanographic modelling at a location close to the entrance of the Shannon Estuary for (a) the A-IBI-OWR wave model, (b) the Mike-21 extension of the wave model, (c) the ROMS current speed model and (d) the Mike-21 extension of the current speed model. Location of Moneypoint (MP) Jetty included for reference.

4.3 Site suitability

The results of running the site suitability MCDA model to which all of the data was fed, showed significant potential for wet storage of fully integrated FOWTs only at three locations in the study area. These are the Shannon Estuary in the west, Bantry Bay in the south and Belfast Lough in the north (Figure 4a), with potential areas of 3,529 Ha, 5,540 Ha and 2,697 Ha respectively (Table 6). The wind speed threshold of 30m/s (50-year return) was not exceeded at any of these locations. The potential areas at each of these locations are shown in more detail at different depth thresholds from Figure 4b to Figure 4d and are described in more detail below.

The Shannon Estuary (Figure 4b) provides adequate wave shelter (<2m 50-year Hs) inside Kilcredaun Point. The most notable area exceeding the max current speed of 2m/s here is at a location known as the 'Tarbert Race' along the southwestern tip of Labasheeda. Other notable exclusions include those associated with designated anchorage areas southwest of Kilrush, cross river cables east of Moneypoint and the shipping lane running the length of the estuary.

At Bantry Bay (Figure 4c), adequate wave shelter is reached approximately south of Adrigole Harbour. The max current velocity is not exceeded in Bantry Bay. Areas of exposed bedrock present exclusions north of Gerahies in the southeast of the bay. Other exclusions are associated with the designated shipping lane and restricted areas in the east (close to Whiddy Island) as well as aquaculture sites along the north and south shores of the bay.

Areas of potential at Belfast Lough (Figure 4d) lie predominantly outside the harbour's confined port jurisdiction area, extending east toward the north channel due to this being a more sheltered region generally in comparison to Atlantic areas. The 2m 50-year Hs conditions are not exceeded until the outer extent of the lough, north of Ballymacormick Point. The max peak current velocity limit is not exceeded in Belfast Lough. Other evident exclusions include those associated with the shipping channel and subsea cables running in an east-west direction.

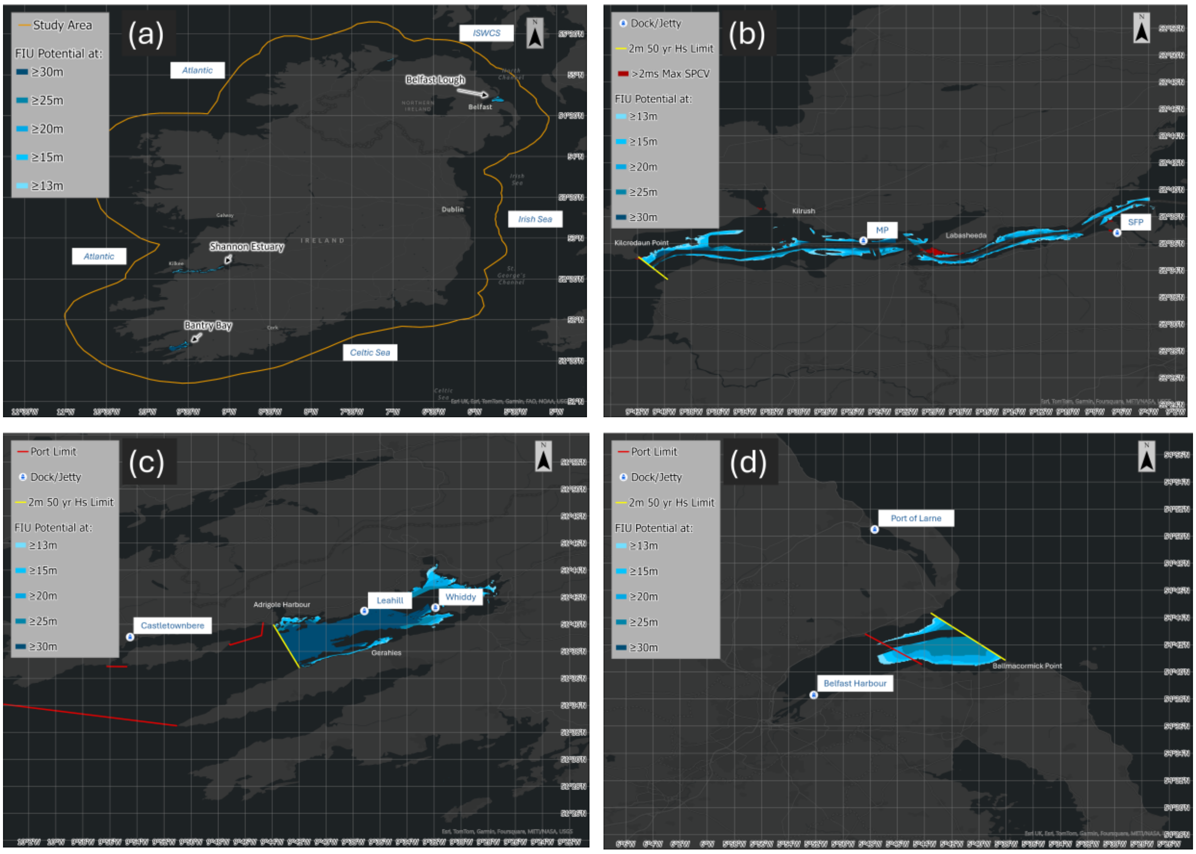

Figure 4. The Wet-Storage site suitability results at (a) national extent, (b) the Shannon Estuary, (c), Bantry Bay and (d) Belfast Lough. Locations of ports/jetties included for reference.

Table 6. Wet storage area of potential in hectares.

Shannon Estuary	Bantry Bay	Belfast Lough
3,529 Ha	5,540 Ha	2,697 Ha

5. Conclusion

Ireland's vast offshore wind potential, particularly in the deeper waters off the west coast, presents a transformative opportunity for renewable energy generation in this region. This study discusses the critical need for Ireland to invest in port infrastructure at the right locations to support FOW deployment and ensure timely project execution whilst maximising regional economic benefits. Logistically, wet storage has been identified as a key enabler for developing FOW projects out of Ireland due to the narrow weather window availability expected on the Atlantic seaboard, requiring FOWTs to be stored in port until deployment becomes possible.

Through the detailed met-ocean data analysis, model validation, and site suitability assessments performed, three key locations (the Shannon Estuary, Bantry Bay and Belfast Lough) have been identified as the only viable areas for wet storage of FOWTs in Ireland. Consequentially, focusing resources and future port development at these specific locations, which have the appropriate geographical attributes, will help to address these infrastructural gaps timely and efficiently. This will be essential for Ireland to harness its full offshore wind potential in deeper waters, meeting its renewable energy targets, and setting its position as a leader in Europe's renewable energy transition.

In terms of future work, further investigation of the wave model underestimations for extreme values (when compared to in-situ data) is warranted. A validation of the current speed model used would be valuable if an appropriate in-situ data source close to the areas of interest is available. Additionally, application of this data and methodology to other regions with plans for FOW development in the coming years would be beneficial for identifying suitable areas/ports for wet storage there, particularly in areas with similar weather window concerns.

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