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Combined renewable resource exploitation: Implications for the all-island Irish electricity supply system

Hafiz Ahsan Said *, Agustina Skiarski, John V. Ringwood

Centre for Ocean Energy Research (COER), Department of Electronic Engineering, Maynooth University, Maynooth, W23 F2H6, Co. Kildare, Ireland

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ABSTRACT

Most countries are increasingly focusing on the exploitation of combined renewable energy resources and balancing storage modalities to drive future power networks entirely with renewable generation. The transition plan, particularly in Ireland, is primarily driven by wind and solar energy, in combination with hydrogen storage. In this paper, we assess the full gamut of combined resource exploitation, focusing on the potential benefits of combining the relatively unexploited but significant marine renewable energy resources (wave and tidal) with more established renewable technologies, such as wind and solar. Specifically, this paper presents a complementarity assessment of four renewable resources, i.e. wave, tidal, wind, and solar, around the Island of Ireland, including Northern Ireland. The complementarity results demonstrate clear benefits of diversifying the resource mix, with the highest complementarity achieved by combining all four resources. Furthermore, we conduct an optimal storage sizing analysis for various resource combinations, considering both 100% renewable and transitional scenarios. This analysis reveals that maintaining some level of fossil-fuel generation, though non-ideal from a climate action perspective, may be beneficial in terms of the required storage size, and associated costs. Based on the optimal storage sizing results, we perform a techno-economic feasibility analysis for different storage modalities, finding that hydrogen storage may not be the best option for Ireland due to its lower cycle (turn-around) efficiency compared to other storage technologies. However, hydrogen can be directly used in other applications, such as transport and industry. Finally, we discuss the implications of these findings within the context of the all-island Irish electricity supply system, considering operational aspects, resource evolution, and policy considerations.

1. Introduction

To mitigate the adverse effects of anthropogenic climate change, countries are increasingly turning towards renewable energy sources (RESs) as essential alternatives for decarbonisation. Ambitious goals, such as achieving zero emissions and a 100% renewable future, are gaining traction. For example, the European Union (EU) aims to increase the share of renewables in its overall energy supply, raising the binding target for 2030 to 42.5%, with the aim of reaching 45% under the revised Renewable Energy Directive [1]. Similarly, Ireland has set ambitious plans in its National Energy and Climate Plan (NECP 2021–2030) [2], aiming to increase the share of renewables to 70% by 2030, representing a 324% increase over the period from 2018 to 2030.

Currently, this *green revolution* is driven primarily by established wind and solar energy worldwide [3], and primarily wind energy in Ireland [4]. For instance, in 2023, a record 35% of the all-island (Ireland and Northern Ireland) load demand was met by wind energy alone [5]. However, relying solely on one (or two) RESs may not be optimal, as RESs are inherently weather-dependent and intermittent. Consequently, periods without wind or sun can have a detrimental impact on electricity supply systems, requiring balancing through storage and/or fossil-fuel plants. For example, the electricity system in Ireland experienced an *amber alert* in June 2023 [6], warning of a potential shortfall in supply due to a combination of low wind and solar power, and outages at several generators. To address this, the incorporation of new forms of renewable energy, such as wave (though not yet commercially viable) and tidal energy, into the current generation mix, aids in the transition to a fully 100% renewable energy future, given the abundance of such resources [7]. Additionally, the International Energy Agency (IEA) identifies that 75% of the CO_2 emissions reduction required for long-term decarbonisation needs to come from technologies that are not yet commercially deployed [8].

Ireland can benefit from such combined resource exploitation due to its island topography and enviable marine energy resources, which potentially provide complementary benefits to the more established

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* Corresponding author.
E-mail addresses: Hafiz.AhsanSaid@mu.ie (H.A. Said), agustina.skiarski.2024@mumail.ie (A. Skiarski), john.ringwood@mu.ie (J.V. Ringwood).

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wind and solar resources [9,10]. However, it is worth noting that even a high diversity of RESs generation may not be sufficient to meet the ever-fluctuating load demand. In this regard, energy storage is the essential *glue* that reconciles the mismatches between generation and load requirements for a future 100% renewable energy supply system. Furthermore, Ireland faces unique energy system constraints that heighten the need for diverse renewable integration. With limited interconnection to mainland Europe, the Irish grid relies primarily on domestic generation. At present, there are only three interconnectors in operation: two connecting Ireland and Wales (the East-West Interconnector (EWIC) and Greenlink) and one linking Northern Ireland and Scotland (Moyle). Together, these interconnectors provide a total exchange capacity of 1.5 [GW], which accounts for around 20% of all-Ireland peak electricity demand of ∼ 7.5 [GW], restricting Ireland's ability to import or export electricity during periods of supply/demand imbalance. Compounding this challenge, data centres now account for approximately 18% of Ireland's total electricity demand [11], significantly increasing grid strain and amplifying the need for reliable, dispatchable renewable generation and storage solutions. Therefore, storage sizing is crucial to improve the *timing-value* of these variable RESs. This paper examines such timing-value by analysing temporal complementarity among four RESs, such as wind, solar, wave, and tidal sources for the Island of Ireland (IoI). Previous studies on Ireland explore pathways to a 100% renewable future, including heating, energy, and transport sectors [12–14]. However, it should be noted that the energy storage requirements in these modelling frameworks is underestimated, due to the use of lower temporal resolution data [14], since these studies focus on long-term pathways rather than estimating the size (cost) of storage associated with 100% RES generation. Significantly, this paper also focuses on optimal storage sizing analysis, for various generation scenarios utilising high temporal resolution (hourly) data, including 100% renewable energy generation and transitional scenarios (with some level of fossil-fuel generation), in addition to the complementarity analysis.

From a more global perspective, a variety of studies in the literature explore political, technical and economical pathways to 100% renewable scenarios for various jurisdictions, such as the US [15], Asia [16], Europe [17], and Australia [18]. A comprehensive review of such studies is presented in [19]. Each study tackles specific aspects and sectors of a 100% renewable energy future, e.g. feasibility [20], optimal storage/balancing requirement [17], issues related to the surplus generation with increasing RES penetration [15], and complementarity [21], to name a few. Regarding storage sizing for renewable injection, [15,17,21–28] are relevant. In particular, [17] provides a seasonal optimal mix considering only wind and solar, utilising relatively lower (monthly) resolution data, which is then extended in [22] by using hourly resolution data, resulting in a different optimal mix due to intra-day data variations. Authors in [24] included run-of-river power plants, in addition to solar and wind, to assess the capability of such hydro plants to improve RES penetration and reduce storage costs. However, the analysis results in an *unrealistic* contribution from run-of-river power plants for some locations, owing to technical and economic feasibility reasons, since the analysis does not include any constraints on the capacity of each resource. The same analysis is extended in [25], for a region in Northern Italy, to assess the role of the horological prediction method in the analysis. In [27,28], techno-economic aspects of storage sizing for ocean RES farms are discussed; however, only two RESs, i.e. offshore wind and wave energy, are considered. While these studies provide valuable insights into offshore renewables, they do not capture the full range of resources available for an islanded energy system. In contrast, this paper incorporates four renewable resources: wind, solar, wave, and tidal, providing a comprehensive analysis of resource complementarity and storage requirements. Recent efforts have been made to assess the temporal complementarity of more than two resources, including marine renewable energy resources (wave and tidal) for US and UK jurisdictions [21,26], concluding that marine renewable resources may have significant value to future power systems, in terms of reduced balancing requirements and valuable capacity contribution. However, all studies use normalised (to the load demand) data for storage sizing (balancing cost) analysis, which does not allow for the implementation of constraints on the capacity of each individual resource. In contrast, this paper presents a storage sizing approach, which does not require normalisation of the resource and load data. Consequently, the proposed approach allows for the implementation of constraints on the resource capacity, ensuring the feasibility of the optimal resource mix solution. Furthermore, the use of high-temporal-resolution data (hourly) enables a more accurate representation of intra-day fluctuations compared to studies relying on monthly or seasonal data, such as [17]. This approach provides a more realistic assessment of storage needs and system balancing requirements.

The main contributions of this paper are summarised as follows:

- This paper presents a complementarity analysis of four resources, i.e. wind, solar, wave, and tidal, using new complementarity metrics, which allow for assessing complementarity for more than two resources simultaneously, and extends the analysis presented in [10] to five years (2018–2022) of data for each resource.
- Moreover, an optimal storage sizing assessment for the all-island Irish load demand, considering both 100% renewable energy and transitional scenarios that include some level of fossil-fuel generation, is presented in this paper. Unlike previous studies that rely on normalised data, the proposed approach does not normalise data for storage sizing analysis, enabling explicit constraint implementation on each resource contribution, ensuring the feasibility of the optimised resource mix.
- Based on the results of the storage sizing analysis, this paper presents a techno-economic feasibility analysis for different storage modalities for the IoI.
- Finally, a discussion is included, which considers the implications of the presented analysis for the all-island Irish electricity supply system.

The remainder of the paper is structured as follows: Section 2 presents data collation, including the choice of locations around the IoI and power generation models for each renewable energy source. Section 3 details temporal complementarity measures, analysis, and results, while Section 4 presents optimal storage sizing assessment, including sizing methodology, consequent results and techno-economic feasibility for various storage technologies. Section 5 provides a comprehensive discussion on the implications of the results for the Irish supply system, while Section 6 concludes this study.

2. Data collation and power generation models

This section details the data collation, including resource data for each renewable modality and load demand data, for the IoI. In addition, power time-series generation models for each resource are also presented here.

2.1. Resource data

As previously mentioned in Section 1, the four RESs under study are solar, wind, tidal current and wave resources. In order to assess their potential on the IoI, this study uses time-series data of 11 different locations distributed across the island, to account for the variations of the resource in both time and space. The data was obtained from two sources: the ERA5 database [29] for the wind, wave and solar resources, and the Irish Marine Institute [30] for the tidal current resource. The ERA5 database is the fifth generation of atmospheric reanalysis produced by the ECMWF (European Centre for Medium-Range Weather Forecasts), which combines model data with observation, resulting in

Table 1
Description of the data variables collected for each resource.

Resource	Time-series data	Source
Wind	Wind velocity, eastward and northward components [$\frac{\text{m}}{\text{s}}$]	ERA5 [29]
Solar	Mean surface radiation flux [$\frac{\text{W}}{\text{m}^2}$], Surface temperature [K]	ERA5 [29]
Wave	Mean wave period [s], Significant wave height [m]	ERA5 [29]
Tidal	Surface current velocity, eastward and northward components [$\frac{\text{m}}{\text{s}}$]	Marine Institute [30]

Table 2
Latitude and longitude (in degrees) of data points for each dataset.

Location	ERA5 (wind and solar)	ERA5 (wave)	Marine Institute
Inishtrahull Sound	55, −7.5	55, −9	55.0996, −7.5051
North East Coast	55, −6.5	55, −5.5	55.218, −6.5541
Copeland Islands	54.5, −5.5	54.5, −5	54.6769, −5.4876
Codling Arklow Banks	53, −6.5	53, −5.5	53.0038, −6.0387
Carnsore Point	52.5, −6.5	52, −6	52.4382, −6.3151
Gascanane Sound	52, −9.5	51, −9.5	51.809, −9.7965
Dursey Sound	52, −10	52, −13	52.0446, −10.0228
Strangford Lough	54.5, −5.5	54.5, −5	54.5121, −5.4526
Lough Foyle	55, −7	54.5, −9	55.1743, −6.8887
Shannon Estuary	52.5, −9.5	52.5, −13	52.5377, −9.4276
Bulls Mouth	54, −10	54, −13	54.0253, −10.0118

hourly estimates of atmospheric, ocean-wave and land-surface variables. The data from Marine Institute corresponds to modelled currents, based on the ROMS (Regional Ocean Modelling System) hydrodynamic model. Table 1 summarises the data collected for each resource. The data span a five year period, from January 1st 2018 to December 31st 2022, with hourly resolution.

In this study, data locations are selected by identifying potential tidal sites around the IoI [31], since the tidal resource is relatively more limited, in terms of both availability and measurement points, compared to wind, solar, and wave resources, which are present across most coastal locations in IoI. The locations for the datasets, depicted by coloured circles, are shown in Fig. 1. Table 2 shows the data points selected for each dataset. The ERA5 wave resource dataset has a lower resolution than the other datasets, therefore the closest available data points to each of the 11 locations were selected, avoiding spatial interpolation. Although the selection of various locations across the IoI provides spatial diversity, some degree of correlation remains among the resources, as individual weather systems can influence the entire island. However, an exception to this inter-resource correlation is the wave resource on the West Coast which, in general, has low correlation with other resources, since the Atlantic swell is typically generated mid-Atlantic.

2.2. Load data

The electrical load demand data for the IoI is obtained from the Entsoe Transparency Platform [32] for the period 2018–2022. This dataset, originally with a 30 min time step, is down-sampled by averaging two consecutive values at each hour to ensure that the load data resolution matches that of the resources data. Any missing values in the dataset are addressed by substituting them with the corresponding load value from the previous day at the same hour. The load curve was then scaled up to account for transmission and distribution system losses, estimated at 8% of the total power demand, as reported in the All-Island Generation Capacity Statement 2022–2031 [33]. Fig. 2 shows the resulting demand curve used for this study.

2.3. Power generation models

The power generation models, also described in [10], are utilised in this study to compute the output power time-series given by each resource (wave, wind, solar, and tidal current). To keep the paper reasonably self-contained, in the following subsections, we briefly describe each model.

2.3.1. Wave energy converter model

The wave power generation model is based on the 750 [kW] Pelamis wave energy converter (WEC) [34]. The power production of the Pelamis is described in a published power matrix, as depicted in Fig. 3, which, though subject to generic concerns regarding power matrix representations [35], provides a reliable basis for analysis and comparison in this study with simplicity and computability as priorities. Using the wave period and significant wave height at each time step as inputs, the power matrix gives the corresponding power generated by the WEC.

2.3.2. Wind turbine model

The maturity of wind turbine technology enables the utilisation of well-established power curves. For this study, a representative W2E-215/9.0 (9 [MW]) [36] wind turbine is selected, with the associated power curve depicted in Fig. 4. Using the wind speed at each time step as input, the power curve gives the corresponding power generated by the wind turbine.

2.3.3. Solar panel model

The electricity generated by a solar panel relies on the global solar irradiance or the surface radiation flux (G_{irr}) and the air temperature (T_{air}) [23], along with the efficiency of the photovoltaic (PV) panel. This relationship can be expressed [37] using:

$$P_{\text{solar}} = \eta_p G_{\text{irr}}(t) \left[1 - \mu(T_{\text{air}} - T_{\text{STC}}) - \mu C G_{\text{irr}}(t)\right], \tag{1}$$

where η_p represents a constant production parameter, which is the product of PV array surface area and inverter (and generator) efficiencies. μ and C are the efficiency reduction factors depending on the temperature and irradiance, respectively. T_{STC} is the standard test condition temperature corresponding to the photovoltaic cell [38]. The solar panel used in this study is the JA Solar JAM72S30-535 (535 [W]) [39].

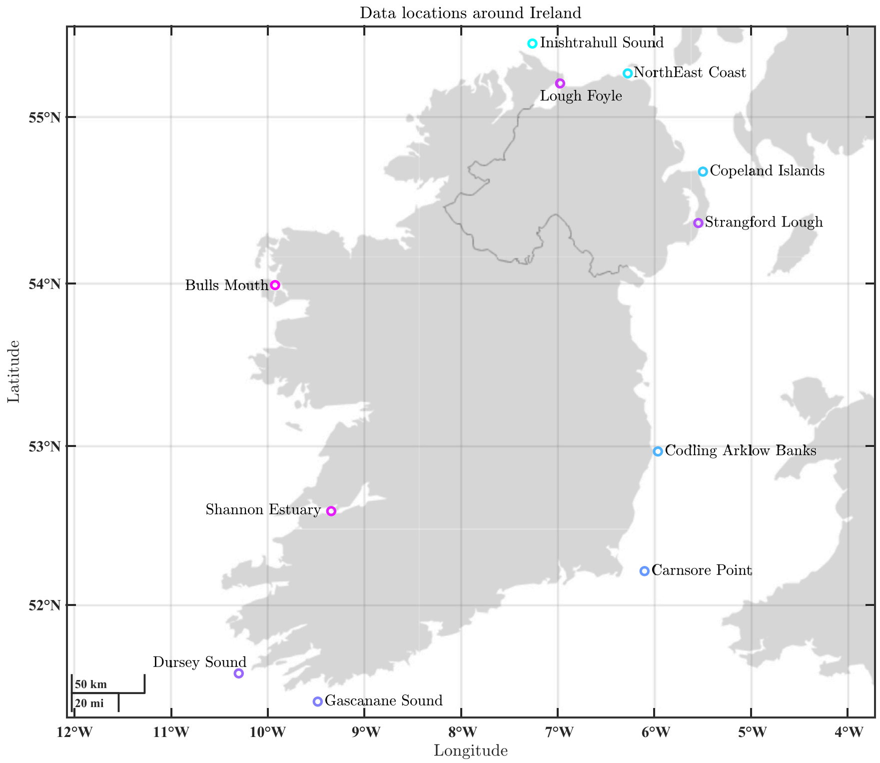


Fig. 1. Choice of data measurement points around Island of Ireland.

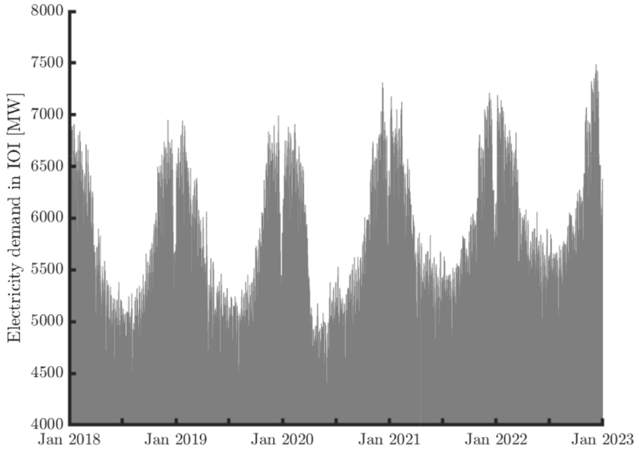


Fig. 2. Hourly load data for Island of Ireland from the period 2018–2022.

2.3.4. Tidal turbine model

In this study, the tidal devices employed to model the conversion of tidal kinetic energy into electrical power are similar to marine versions of well-established horizontal-axis wind turbines. As in the wind model, the power output of the tidal turbine is modelled using a power curve, where the input is the tidal stream velocity. Fig. 5 shows a generic 1200 [kW] tidal turbine power curve used in this study.

3. Complementarity analysis

The concept of *energetic complementarity* refers to the synergistic integration of multiple variable renewable energy sources to enhance system reliability and minimise periods of energy shortfall. Evaluating complementarity among various renewable modalities is essential for designing an efficient and dependable energy mix that meets load requirements within a jurisdiction. Traditionally, complementarity is associated with *negative correlation*. However, utilising correlation for complementarity assessment has significant limitations, particularly in assessing the complementarity of more than two resources, as it only allows for calculations involving two resources at a time, among other issues highlighted in [40]. New complementarity metrics, based on total variation, standard deviation, and variance, have been proposed to address the limitations identified in [40]. In particular, these new metrics offer the advantage of evaluating complementarity among more than two resources. Each metric is briefly discussed in the following subsection.

3.1. Complementarity metrics

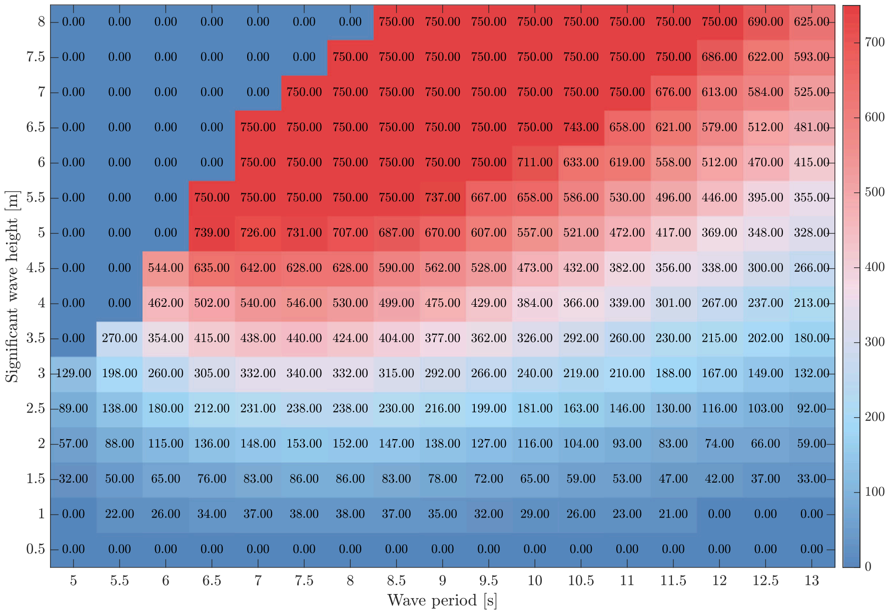
(a) Total variation complementarity index, Φ: This index is grounded in the mathematical concept of total variation. For n functions f_i, $\forall\ i = 1, 2, \ldots, n$, the general formulation of Φ over a time interval $[a, b]$ is given by:

$$\Phi(f_i) = 1 - \frac{\bigvee\limits_{b}^{a}(f_1 + f_2 + \cdots + f_n)}{\bigvee\limits_{b}^{a}(f_1) + \bigvee\limits_{b}^{a}(f_2) + \cdots + \bigvee\limits_{b}^{a}(f_n)}, \tag{2}$$

where

$$\bigvee\limits_{b}^{a} = \sup \sum_{j=1}^{m} |f(t_j) - f(t_{j-1})|, \tag{3}$$

represents the total variation of a function $f(t)$. The supremum is taken over all possible finite partitions $a = t_1 < \cdots < t_n = b$ of $[a, b]$. The complementarity index $\Phi(f_i)$ ranges from 0 to 1, where $\Phi(f_i) = 1$ indicates perfect complementarity, and $\Phi(f_i) = 0$ signifies no complementarity (analogous to a high level of correlation). For a detailed discussion on the characteristics of this metric, readers are referred to [40].



	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10	10.5	11	11.5	12	12.5	13
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	690.00	625.00
7.5	0.00	0.00	0.00	0.00	0.00	0.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	686.00	622.00	593.00
7	0.00	0.00	0.00	0.00	0.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	676.00	613.00	584.00	525.00
6.5	0.00	0.00	0.00	0.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	743.00	658.00	621.00	579.00	512.00	481.00
6	0.00	0.00	0.00	0.00	750.00	750.00	750.00	750.00	750.00	750.00	711.00	633.00	619.00	558.00	512.00	470.00	415.00
5.5	0.00	0.00	0.00	750.00	750.00	750.00	750.00	750.00	737.00	667.00	658.00	586.00	530.00	496.00	446.00	395.00	355.00
5	0.00	0.00	0.00	739.00	726.00	731.00	707.00	687.00	670.00	607.00	557.00	521.00	472.00	417.00	369.00	348.00	328.00
4.5	0.00	0.00	544.00	635.00	642.00	628.00	628.00	590.00	562.00	528.00	473.00	432.00	382.00	356.00	338.00	300.00	266.00
4	0.00	0.00	462.00	502.00	540.00	546.00	530.00	499.00	475.00	429.00	384.00	366.00	339.00	301.00	267.00	237.00	213.00
3.5	0.00	270.00	354.00	415.00	438.00	440.00	424.00	404.00	377.00	362.00	326.00	292.00	260.00	230.00	215.00	202.00	180.00
3	129.00	198.00	260.00	305.00	332.00	340.00	332.00	315.00	292.00	266.00	240.00	219.00	210.00	188.00	167.00	149.00	132.00
2.5	89.00	138.00	180.00	212.00	231.00	238.00	238.00	230.00	216.00	199.00	181.00	163.00	146.00	130.00	116.00	103.00	92.00
2	57.00	88.00	115.00	136.00	148.00	153.00	152.00	147.00	138.00	127.00	116.00	104.00	93.00	83.00	74.00	66.00	59.00
1.5	32.00	50.00	65.00	76.00	83.00	86.00	86.00	83.00	78.00	72.00	65.00	59.00	53.00	47.00	42.00	37.00	33.00
1	0.00	22.00	26.00	34.00	37.00	38.00	38.00	37.00	35.00	32.00	29.00	26.00	23.00	21.00	0.00	0.00	0.00
0.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Fig. 3. Power matrix for the 750 [kW] Pelamis WEC [34].

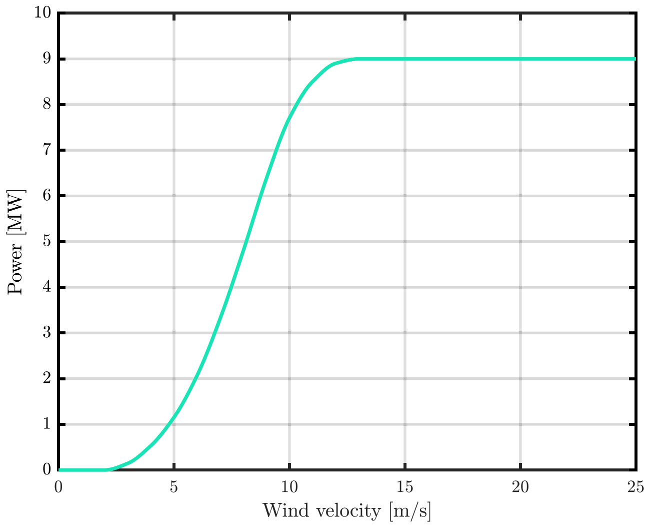


Fig. 4. W2E-215/9.0 (9 [MW]) [36] wind turbine curve utilised in this study.

(b) Variance complementarity index, $\hat{\Phi}$: Adapting Eq. (2) by replacing the total variation with variance (σ^2) results in

$$\Phi_v(f_i) = 1 - \frac{\sigma^2(f_1 + f_2 + \cdots + f_n)}{\sigma^2(f_1) + \sigma^2(f_2) + \cdots + \sigma^2(f_n)}, \tag{4}$$

where $-1 < \Phi_v < 1$. By considering variance, this metric accounts for the variability and spread of the variables, offering a more suitable assessment of complementarity compared to correlation. For consistent analysis with other complementarity indices, Φ_v is re-scaled as follows:

$$\hat{\Phi} = \frac{(\Phi_v + 1)}{2}, \tag{5}$$

where $0 < \hat{\Phi} < 1$. Although $\hat{\Phi}$ was originally designed for only two resources, resulting in a correlation-based metric [40], this article applies the generalised definition in (4) to evaluate complementarity among the four resources.

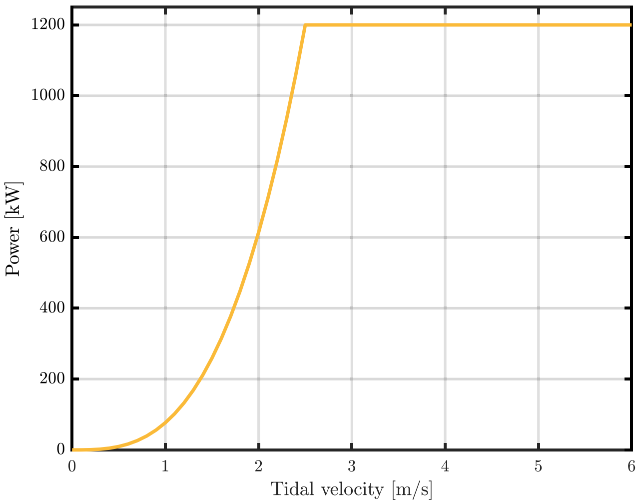


Fig. 5. Generic tidal turbine curve utilised in this study.

(c) Standard deviation complementarity index, Φ_s: Similar to the variance complementarity index, this index, Φ_s, is derived by replacing the total variation in (2) by the standard deviation σ, as:

$$\Phi_s(f_i) = 1 - \frac{\sigma(f_1 + f_2 + \cdots + f_n)}{\sigma(f_1) + \sigma(f_2) + \cdots + \sigma(f_n)}, \tag{6}$$

where $0 < \Phi_s < 1$. The index Φ_s evaluates the variability of the sum using the standard deviation, which retains the same units as the original variables, unlike the squared values used in Φ_v.

3.2. Complementarity analysis results

To illustrate the potential complementarity among resources, the proposed metrics are calculated for various locations across the IoI, considering different time scales and resource combinations. The analysis employs all three complementarity indices, i.e. Φ, Φ_s, and $\hat{\Phi}$. Additionally, the time-series data for each resource is normalised to its maximum value, ensuring a consistent scale for the complementarity

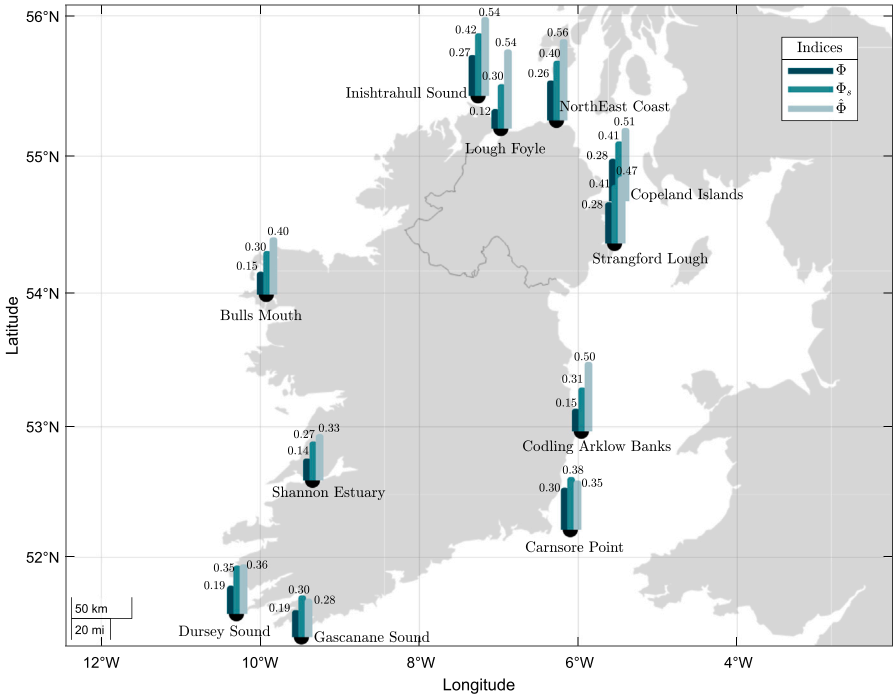


Fig. 6. Complementarity indices for all resources at selected locations around the IoI. Each group of bars represents the complementarity indices value for that location, with different indices distinguished by the colours shown in the legend.

assessment. It is important to note that this normalisation is applied solely for the complementarity analysis, and not for the storage sizing analysis presented in Section 4.

The results showing the complementarity among RESs at each selected location are presented in Fig. 6, which illustrate relatively consistent results across all three complementarity indices albeit with varying level of complementarity for each index. For example, the values of Φ range from 0.14 (Shannon Estuary) to 0.30 (Carnsore Point), with similar trends observed for Φ_s and $\hat{\Phi}$. Each metric indicates that locations in the north-east and south-east of IoI exhibit greater complementarity, primarily due to the greater solar resource combined with lower levels of wind and wave resources in these regions. The results in Fig. 6 highlight that utilising four different resources at a single location can significantly enhance complementarity. Another important observation, from Fig. 6, is that the complementarity metrics, Φ_s and $\hat{\Phi}$, show more sensitivity to data variations and tend to overestimate complementarity, which is consistent with the conclusions drawn in [10,40].

Fig. 7 presents the comparative analysis of the three complementarity metrics on a seasonal timescale, with data combined from all locations to emphasise seasonal trends. The total variation complementarity index, Φ, shows a consistent pattern, with small variations throughout the five years 2018–2022. Interestingly, the metrics Φ_s and $\hat{\Phi}$ exhibit significant *underestimation* of complementarity, compared to Φ, which contrasts with the overestimation observed in Fig. 6, raising concerns about their reliability and effectiveness for accurate complementarity quantification. As recommended by the authors in [40] and shown in Fig. 7, Φ is the preferred metric for quantifying complementarity, since it incorporates the regularity measure of the sum of variables as a core concept in evaluating complementarity.

To illustrate the spatial complementarity of each RES at different locations, total variation complementarity index, Φ, for each of the four resources for combinations of selected locations around IoI are computed. Fig. 8 specifically presents spatial complementarity spider maps for the tidal resource using Φ. Tidal energy is highlighted because it exhibits the highest spatial complementarity values, attributed to the asynchronous timing of peak tidal velocities at different locations across IoI. It is evident, from Fig. 8, the highest complementarity values occur between the North and South coasts of IoI. In addition, Fig. 8 also illustrates that complementarity values are lower between closely situated locations, emphasising the significance of having geographically distributed generation across the IoI to maximise complementarity. For spatial spider maps of other three resources, i.e. wave, wind and solar, readers are referred to Appendix.

Table 3
Complementarity indices for various combinations of resource-mix for island of Ireland.

Resource Mix	Φ	Φ_s	$\hat{\Phi}$
Wave-wind	0.072	0.060	0.252
Wave-tidal	0.064	0.293	0.502
Wave-solar	0.058	0.367	0.600
Wind-tidal	0.200	0.218	0.506
Wind-solar	0.135	0.280	0.562
Tidal-solar	0.140	0.286	0.492
Wave-wind-tidal	0.230	0.224	0.281
Wave-wind-solar	0.170	0.279	0.361
Wave-tidal-solar	0.183	0.463	0.570
Wind-tidal-solar	0.274	0.392	0.560
Wave-wind-tidal-solar	0.296	0.376	0.376

In order to illustrate the impact of resource diversity, i.e. the number of resources in the resource mix, on complementarity, Table 3 presents complementarity metrics, Φ, Φ_s, and $\hat{\Phi}$, for various resource mix combinations. From Table 3, it is clear that increased resource diversity leads to a higher level of complementarity. For instance, taking Φ as an example, the complementarity is lower for mixes with only two resources and gradually increases with the inclusion of a third resource. The highest complementarity is observed when all four resources are included, as indicated by the highlighted green cell in Table 3. Once again, it can be observed that Φ_s and $\hat{\Phi}$ not only tend to either overestimate or underestimate complementarity, compared to Φ, for different resource mixes, but they also exhibit greater sensitivity to the inclusion of new resources to the mix.

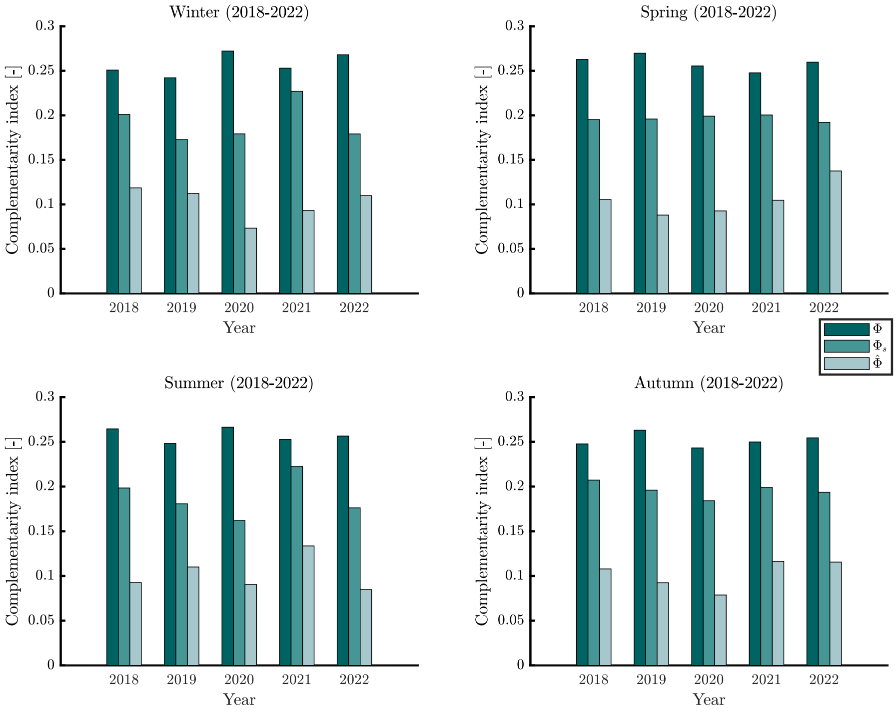


Fig. 7. Seasonal complementarity for 2018–2022 for all resources.

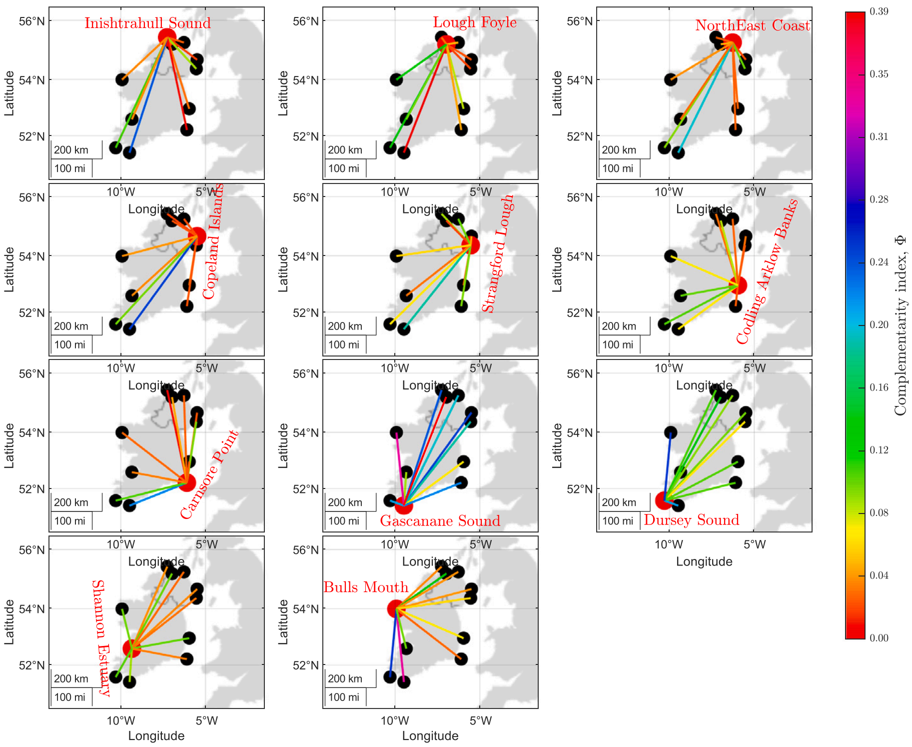


Fig. 8. Spatial complementarity spider maps of tidal resource among combinations of various chosen locations around IoI using total variation complementarity index, Φ. Each subplot shows a spider map for one chosen location highlighted with red dot , with each (colour coded) line representing the complementarity index value between any pair of locations.

The complementarity results highlight the challenges of quantifying complementarity, which has traditionally been assessed through negative correlation—an approach with several limitations (see, e.g., [40]). Furthermore, complementarity among time series is influenced by both cross-correlation and autocorrelation properties [40]. Unlike Φ_s and $\hat{\Phi}$, which primarily capture cross-correlation effects, Φ inherently accounts for both cross-correlation and autocorrelation dependencies. This distinction allows Φ to offer a more comprehensive representation of complementarity. Here, the use of the total variation-based index, Φ, allows for a more consistent assessment of complementarity by focusing on the regularity of the sum of variables, a fundamental aspect in evaluating complementarity. In contrast, the standard deviation and variance-based metrics, Φ_s and $\hat{\Phi}$, are more sensitive to data variations and may therefore be less suitable for complementarity quantification. Moreover, the findings of the complementarity analysis highlight the potential advantages of increasing resource diversity within the generation mix. Enhancing temporal complementarity can reduce reliance on large-scale energy storage solutions. To explore this potential benefit further, the following Section 4 presents an optimal storage sizing analysis.

4. Optimal storage sizing

In this Section, we assess the power generation mix required for 100% renewable generation in the IoI and minimum storage requirements. As previously stated, this analysis is carried out using absolute values of instantaneous power generation and demand (in MW), which allows the effective implementation of constraints on each resource contribution. The instantaneous power generated by each technology (i.e. wind, wave, solar, and tidal) is calculated using the resource time-series data described in Section 2.1 and the power generation models from Section 2.3.

4.1. Storage sizing methodology

The storage sizing analysis is based on a grid search method, where the instantaneous storage requirement is calculated for different scenarios of resource contribution, that is, different installed capacity of each energy technology. First, a maximum resource contribution in MW is defined for each technology, assuming that the installed capacity of each resource is evenly distributed throughout all chosen locations. The maximum contribution for wave, solar and wind is chosen considering the maximum peak power demand of the load time-series and the generation profile of each technology with the resource data and power models presented in Section 2, ensuring that the peak demand can be covered by only one of these technologies. In the case of tidal energy, on the other hand, a maximum contribution of 105.02 [MW] is considered, which is based on the yearly viable tidal resource of 0.92 [TWh/year], as per the estimate from the Sustainable Energy Authority Ireland (SEAI) [31].

Based on the resource and load data presented in Section 2, the optimal energy mix can be quantified using the energy balance variation $\Delta(t)$, expressed as follows:

$$\Delta(t) = P_{\mathrm{mix}}(t) - P_{\mathrm{load}}(t), \tag{7}$$

with,

$$P_{\mathrm{mix}}(t) = \sum_{\mathrm{i}} P_{\mathrm{i}}(t), \tag{8}$$

where $P_{\mathrm{mix}}(t)$ represents the total power generation from a mix of resources, and $P_{\mathrm{load}}(t)$ represents the load demand at time t. The $P_{\mathrm{i}}(t) \in [P_{\mathrm{i}}^{\mathrm{min}}, P_{\mathrm{i}}^{\mathrm{max}}]$ denote the contribution of each resource to the overall generation mix. The subscript i represents each resource, (e.g. wind, solar, wave, tidal, and fossil-fuel), while $P_{\mathrm{i}}^{\mathrm{min}}$ and $P_{\mathrm{i}}^{\mathrm{max}}$ represent minimum and maximum power capacities (constraints) for each resource. In this case, $P_{\mathrm{i}}^{\mathrm{min}} = 0$ for all resources, i.e. no contribution to the generation mix, $P_{\mathrm{mix}}(t)$. The maximum constraint, P_i^{max}, varies for each resource. The maximum tidal capacity $P_{\mathrm{tidal}}^{\mathrm{max}}$ has been set to 105.02 [MW] because of the available resource around the IoI coast [31]. On the other hand, in the case of wind, wave, and solar resources, the capacity factors CF_i of each plant are calculated over the 5 year period under study. Using these capacity factors, the maximum capacity is defined as the installed capacity needed to supply the peak demand on the IoI during this 5 year period:

Table 4
Maximum resource capacity constraints and their respective capacity factors.

Resource	P_i^{max}	CF_i
Wind	17 [GW]	0.45
Solar	60 [GW]	0.125
Wave	62 [GW]	0.12
Tidal	105.02 [MW]	–

$$P_{\mathrm{i}}^{\mathrm{max}} = \frac{P_{\mathrm{load}}^{\mathrm{max}}}{CF_i} \tag{9}$$

Table 4 shows the maximum limits adopted for the installed capacity P_i^{max} of each resource and the capacity factors CF_i.

In this way, a constraint on the maximum resource contribution can be effectively implemented. A simple storage model is then constructed, based on the energy (im)balance $\Delta(t)$, as follows:

$$\mathcal{S}(t) = \mathcal{S}(t-1) + \begin{cases} \eta_{in}\Delta(t) & \text{if } \Delta(t) \geq 0, \\ \eta_{out}\Delta(t) & \text{if } \Delta(t) < 0, \end{cases} \tag{10}$$

where the time-series $\mathcal{S}(t)$ describes the *filling level* of the storage. Surplus generation, when $\Delta(t)$ is positive, is stored with efficiency η_{in}, while a negative mismatch ($\Delta(t) < 0$) results in energy being drawn from the storage with efficiency η_{out}. For an ideal storage system, $\eta_{in} = \eta_{out} = 1$, while $\eta_{in} = \eta_{out} = 0.9$ for pumped hydro storage (PHS) and $\eta_{in} = \eta_{out} = 0.6$ for hydrogen (H_2) storage (see, for example, Table 5 for efficiencies of different storage modalities). The maximum and minimum values of $\mathcal{S}(t)$ determine the required storage capacity $\mathcal{S}_{cap}$ as:

$$\mathcal{S}_{cap} = \max\{\mathcal{S}(t)\} - \min\{\mathcal{S}(t)\}, \tag{11}$$

where $\max\{\cdot\}$ and $\min\{\cdot\}$ represent the maximum and minimum operators, respectively.

The resulting optimal storage sizing problem is defined as follows:

$$\mathcal{S}_{cap}^{opt} = \arg \min_{P_{\mathrm{mix}}(t)} \mathcal{S}_{cap},$$

subject to:

$$\begin{aligned} &P_{\mathrm{wind}}(t) \in [0, P_{\mathrm{wind}}^{\mathrm{max}}], \\ &P_{\mathrm{solar}}(t) \in [0, P_{\mathrm{solar}}^{\mathrm{max}}], \\ &P_{\mathrm{wave}}(t) \in [0, P_{\mathrm{wave}}^{\mathrm{max}}], \\ &P_{\mathrm{tidal}}(t) \in [0, P_{\mathrm{tidal}}^{\mathrm{max}}]. \end{aligned} \tag{12}$$

Note that, since the time step adopted in this study is 1 h, the power output of each technology is assumed in steady-state, meaning that the generators ramp rate is not accounted for.

4.2. Storage sizing results

Based on the storage sizing methodology presented in Section 4.1, the storage requirements and optimal generation mix are determined for both the 100% renewable energy and fractional/transitional scenarios. Specifically, for the 100% renewable energy case, over 46,000 resource combinations were analysed to identify the optimal mix that minimises storage requirements. To this end, Fig. 9 illustrates the storage sizing results, highlighting six representative combinations from the extensive set of tested scenarios. These combinations highlight the wide range of storage requirements, from a minimum of approximately 6 [TWh] to as high as 50 [TWh], for different combinations of RESs capacities. For the minimum storage size, the resultant optimal resource combination comprises 7.65 [GW] of wind, 15 [GW] of solar, 3.1 [GW] of wave, and 26 [MW] of tidal generation, as highlighted by the thick blue line in Fig. 9. These findings offer two key insights from a balancing storage sizing perspective: (a) Incorporating marine

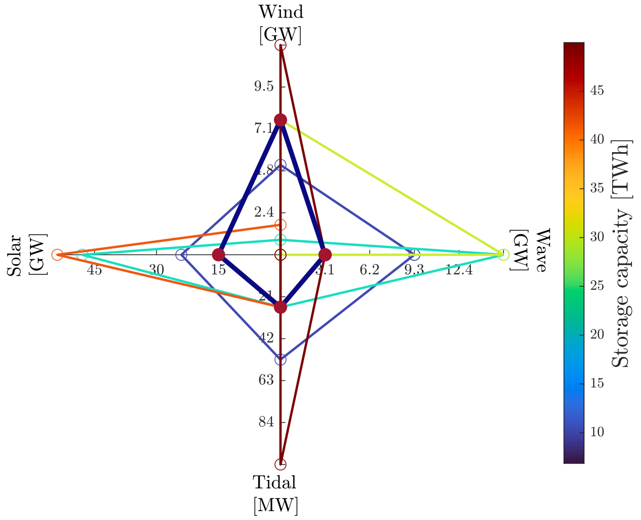


Fig. 9. A subset of combinations of wave, wind, tidal, and solar power plant capacities and their corresponding storage requirements is displayed on a spider plot. The highlighted combination, indicated by a thick blue line, represents the optimal resource mix for the minimum storage requirement. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

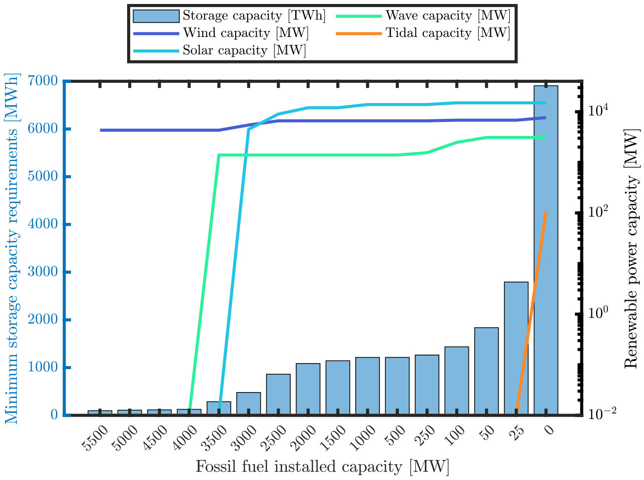


Fig. 10. Optimal (minimum) storage requirements and resource-mix combinations for various transitional scenarios with decreasing levels of fossil-fuel power generation.

resources, such as wave and tidal energy, into the generation mix reduces the required balancing storage, reinforcing the complementarity results (see Table 3), which demonstrate that greater resource diversity enhances complementarity; and (b) a change in contribution from a certain threshold, i.e. 7.65 [GW] for wind energy capacity, requires more storage, regardless of the capacity from other sources. Therefore, an optimal combination of diverse energy resources is crucial to minimise the requirements for balancing storage.

An optimal storage sizing analysis is also conducted for transitional/fractional scenarios, where a level of fossil-fuel generation is part of the optimal mix. In other words, $P_{\text{mix}}(t)$ in (8) includes a constant fossil-fuel contribution, in addition to all the renewable energy capacities. The testing scenarios are based on a single fossil-fuel contribution which starts with the current installed capacity of fossil fuelled power plants in Ireland, i.e. ≈ 6 [GW], and gradually decreases to zero. Fig. 10 presents results for the transitional scenarios with decreasing level of fossil-fuel generation, which illustrate that the need for storage decreases as fossil-fuel generation remains in the mix since the fossil-fuel generation provides base load power. Initially, when fossil-fuel generation decreases from 6 [GW] to 4 [GW], a small amount of storage size is required to meet the load demand, with only renewable contribution coming from wind energy. However, a further decrease in fossil-fuel generation to 4 [GW] requires a significant contribution from a combination of RESs, but with relatively small storage size compared to the fully 100% renewable energy scenario. Furthermore, the storage size increases exponentially when fossil-fuel generation goes below 100 [MW], indicating that having some level of fossil-fuel generation in the mix may make more *economic* sense in terms of balancing storage costs, but with obvious implications for carbon emissions. However, the modest 100 MW of fossil-based plant may be deemed acceptable from an overall economic-climate perspective.

4.3. *Techno-economic feasibility analysis*

Although the results presented in Section 4.2 are based on ideal storage technology, where $\eta_{\text{in}} = \eta_{\text{out}} = 1$, it is important to note that the choice of storage efficiency affects only the storage size, and not the optimal resource mix, consistent with the findings in [17]. To demonstrate the variation in storage sizes across different storage technologies, Table 5 compares storage technologies for the minimum storage scenario highlighted in Fig. 9. The parameters used to compare storage technologies are average values of both economic (LCoS and storage size) and technical (volumetric and gravimetric density) factors. In reality, there is quite a spread in cost, efficiency, and energy density for each technology and, in most cases those values change rapidly over the years due to technological improvements. The values in Table 5 are meant to show, qualitatively, how the technologies currently differ from one another.

Table 5 clearly shows that storage capacity is inversely related to round-trip efficiency; lower efficiency leads to a larger storage requirement, and vice versa, as might be expected. Flywheel storage, with the highest round-trip efficiency, results in the smallest capacity requirement. Conversely, H_2 storage has the largest capacity requirement and the highest cost due to its lower round-trip efficiency, constrained by the Carnot efficiency [46]. Though flywheel storage requires the least capacity, pumped hydro storage (PHS) emerges as the most cost-effective option, due to its relatively low LCoS and reasonably good round-trip efficiency.

From a more physical size aspect, however, PHS requires the largest volume and mass, as such systems are composed of large water reservoirs at high elevation. This volume requirement is a limitation for the deployment of PHS on the IoI because of the topography of the island [47], rendering it relatively infeasible. Of course, H_2 storage presents the lowest gravimetric requirements, but its volumetric requirements are comparable to PHS, due to the low density of the gas. However, if H_2 can be pressurised to up to 200 [bar], the volumetric density becomes closer to that of Li-ion batteries [42]. Finally, Table 5 also suggests that CAES and flywheel storage have lower costs than electrochemical storage technologies (Li-ion, NaS and VFRBs), but with larger volume and mass requirements. This is particularly relevant when developing hybrid offshore systems (including storage), where there are physical constraints associated with offshore platforms.

It is worth noting that the storage technologies compared in Table 5 face challenges beyond technical and economic feasibility. For instance, not all storage technologies are at the same technology readiness level (TRL). More mature technologies, such as CAES and PHS, generally have lower LCoS compared to less-mature VRFBs. Additionally, battery technologies face supply chain constraints due to the availability of critical materials required for manufacture [48]. Addressing these challenges is essential for the large-scale deployment of storage technologies in grid-balancing applications. It should be pointed out that there is ongoing development and improvement of storage technologies, but with a great deal of uncertainty. For example, H_2 is seen

Table 5
Comparison of different energy storage technologies for the minimum storage scenario found in Fig. 9, in terms of economic and technical feasibility [28,41–45].

Economic	Storage technology						
	CAES[a]	Flywheel	H_2[b]	Li-ion[c]	NaS[d]	PHS[e]	VRFB[f]
LCoS [44] [€/MWh]	123	185.5	224	332	200	107	380
Efficiency [%]	80	94	38	90	83	76	75
Storage capacity [TWh]	8.6	7.3	18.1	7.6	8.3	9	9.2
Cost [Billion €]	1057	1356	4051	2535	1656	967	3482
Technical							
Volumetric energy density [kWh/m^3]	10.2	50	2.8	297	225	1.25	21.5
Gravimetric energy density [Wh/kg]	20	52.5	39 400	138	195	1.25	40
Volume requirements [m^3]	8.4×10^8	1.46×10^8	64.6×10^8	0.26×10^8	0.37×10^8	72.8×10^8	4.3×10^8
Gravimetric requirements [ton]	4.3×10^8	1.39×10^8	0.0046×10^8	0.56×10^8	0.43×10^8	72.8×10^8	2.3×10^8
Technical feasibility	✓	✓	✓	✓	✓	✗	✓

[a] Compressed air energy storage.
[b] Hydrogen.
[c] Lithium ion.
[d] Sodium sulphur.
[e] Pumped hydro storage.
[f] Vanadium redox flow battery.

as a promising solution, not only for long-term storage by utilising fuel-cells, but also in direct use for transportation and industry, and can utilise the existing gas network infrastructure. Nonetheless, there is still a large capital cost associated with the electrolysis process and the required additional infrastructure. Meanwhile, according to [44], it is expected that, by 2030, capital costs of battery storage technologies should decrease by half for Li-ion, and a third for VRFB, which will significantly decrease the LCoS for these technologies. In particular, a decrease in VRFB capital costs could position these batteries as competitive alternatives to CAES or flywheels, offering comparable economic and technical merit. In addition, hydrogen storage costs will also likely decline, due to improvements in electrolysis efficiency, economies of scale, and reduced costs of renewable electricity used for *green* hydrogen production. However, it is important to note that the variation in economic parameters, such as future LCoS and efficiency improvements, could significantly impact the feasibility of different storage technologies listed in Table 5. Sensitivity analyses on cost and efficiency trends should therefore be incorporated in future studies to evaluate the robustness of storage deployment strategies, under evolving technological and economic conditions. Furthermore, no single storage technology can effectively meet the diverse temporal requirements of grid-balancing. A distributed storage system, similar to distributed generation, is likely to provide a more viable techno-economic solution. This underscores the need for continued development across multiple storage technologies. For a comprehensive review of large-scale grid storage challenges and potential solutions, readers are referred to [48].

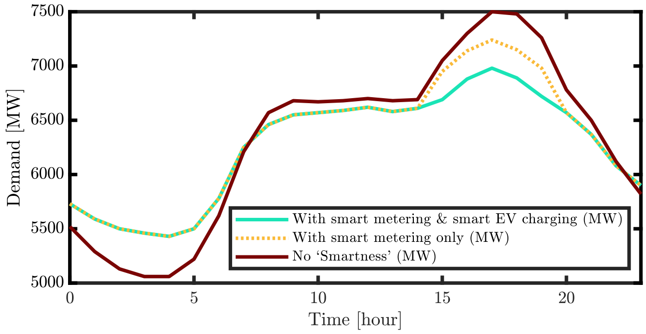


Fig. 11. Impact of smart metering and EV smart charging on the daily demand curve, using a peak day in a 2030 median demand scenario.
Source: Adapted from [33].

5. Discussion

To understand the potential implications of the analysis presented in Sections 3 and 4 for the all-island Irish electricity system, it is crucial to first understand the challenges it currently faces on both the demand and supply (generation) sides. On the demand side, the load demand and daily consumption patterns are changing rapidly. In particular, data centres account for 18% of Ireland's total electricity demand, substantially higher than the European average of 2%, and this figure is projected to rise to a very significant 32% by 2026 [11]. This growth in data centres is placing considerable pressure on the grid, as evidenced by an increase in system alerts since 2021 [49]. Furthermore, the rise in electric vehicle (EV) charging at night may *flatten* the daily consumption curve, effectively raising the base load, essentially by *valley* filling the period of lower demand (see, for example, Fig. 11). On the other hand, the forecasts for rate of change on the supply side are relatively slow, considering the Irish NZE targets. According to the IEA, gas-fired electricity generation is expected to decline by just 0.5% per year until 2026, with strong demand growth limiting more significant reductions. In contrast, renewable energy is projected to grow annually by 13% during this period, driven mainly by wind energy [4].

Considering the context outlined above, our analysis highlights the critical importance of resource diversity in the generation mix to achieve complementarity benefits, specifically in terms of reducing the needs of balancing storage capacity. In particular, our analysis shows that the highest complementarity is achieved when all four RESs are considered. Likewise, the storage sizing analysis supports this result, demonstrating that the optimal resource combination for a 100% renewable generation scenario consists of all four RESs. Under transitional scenarios, with decreasing levels of fossil fuel-based generation, a mix of wind, solar, and wave energy results in the lowest storage needs (noting that tidal is capacity limited). It is important to note that, while marine renewable energy sources, particularly wave energy, are currently not as commercially competitive as wind and solar, comparisons to other RESs, solely on their levelised cost of energy (LCoE) or marginal costs, may not fully capture the *value* of these resources, as evidenced by our findings. Marine resources can contribute significantly to system reliability and balancing, which is essential, given the changing electricity demand landscape in Ireland. Moreover, through the Strategic Energy Technology (SET) Plan [50], the EU has set ambitious cost-reduction targets for ocean technologies, anticipating the need for a diverse energy system. Tidal stream technology costs are expected to decrease to €0.15/kWh by 2025 and €0.10/kWh by 2030, while wave energy costs should fall to €0.20/kWh by 2025

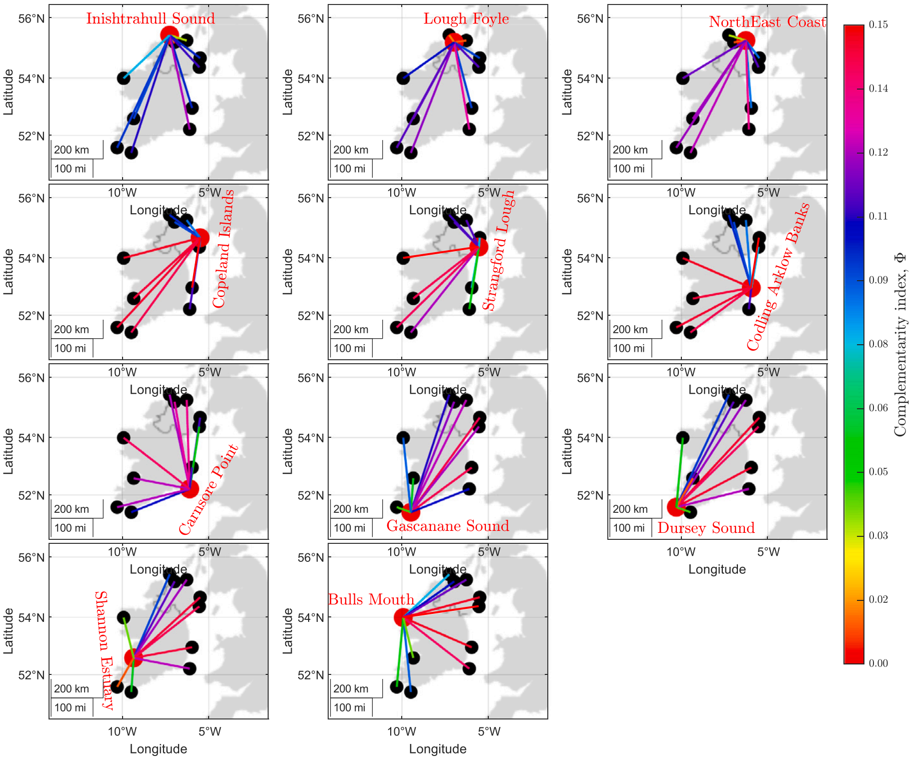


Fig. A.12. Spatial complementarity spider maps of wave resource among combinations of various chosen locations around IoI using total variation complementarity index, Φ. Each subplot shows a spider map for one chosen location highlighted with red dot , with each (colour coded) line representing the complementarity index value between any pair of locations.

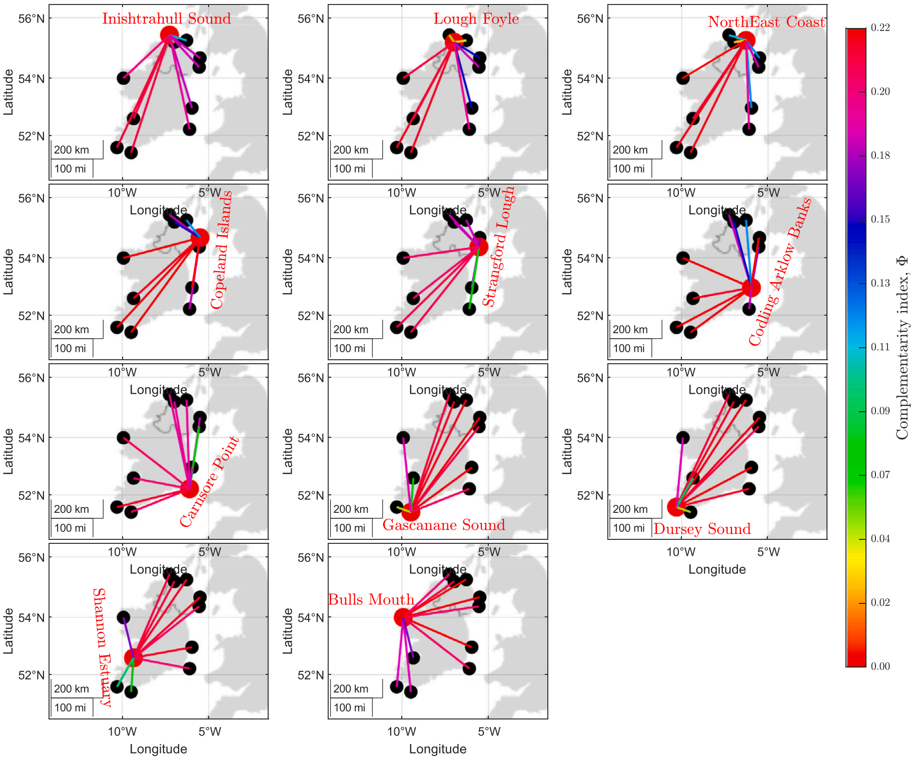


Fig. A.13. Spatial complementarity spider maps of wind resource among combinations of various chosen locations around IoI using total variation complementarity index, Φ. Each subplot shows a spider map for one chosen location highlighted with red dot , with each (colour coded) line representing the complementarity index value between any pair of locations.

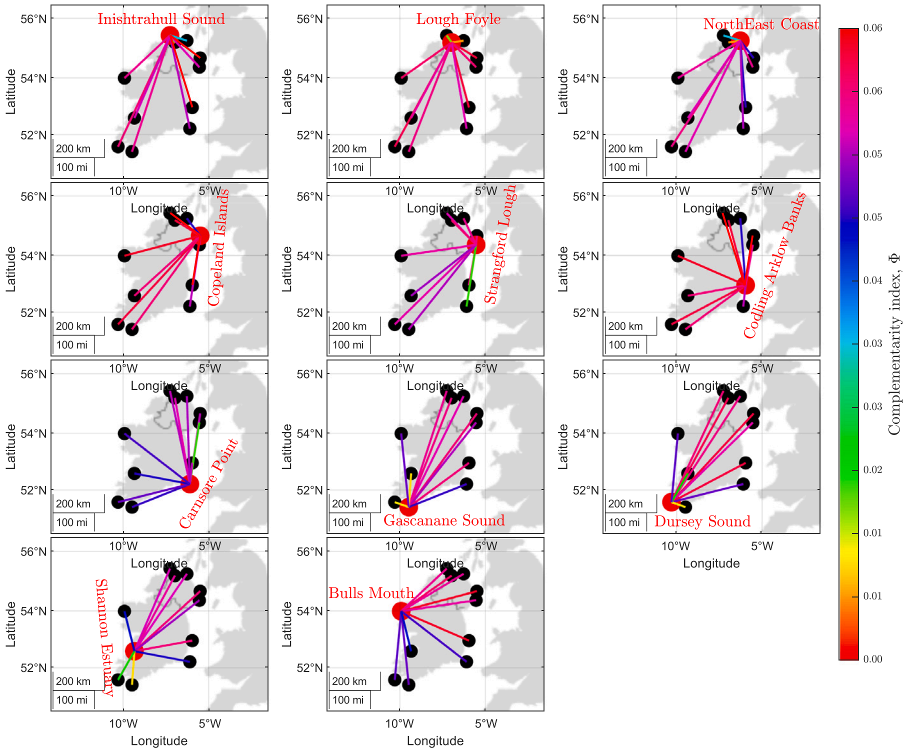


Fig. A.14. Spatial complementarity spider maps of solar resource among combinations of various chosen locations around IoI using total variation complementarity index, Φ. Each subplot shows a spider map for one chosen location highlighted with red dot , with each (colour coded) line representing the complementarity index value between any pair of locations.

and €0.15/kWh by 2030. Therefore, considering the evolving load and generation scenarios, diversity in the supply system is imperative to fully realise the potential benefits (balancing, reliability, etc.) of combined resource exploitation, and to avoid future system alerts.

Achieving a 100% renewable electricity future necessitates the integration of robust storage systems to address the intermittency and weather dependency of RESs, as well as the variability in load demand. Our analysis shows that the storage size required for 100% renewable generation is significantly greater than the transitional scenarios, irrespective of the storage technology considered. Furthermore, our proposed storage sizing approach ensures that the optimal resource mix respects the capacity constraints of each resource in both 100% renewable and transitional scenarios. The choice of specific storage technology (or technologies) for a 100% renewable future requires several considerations. From a power-balancing perspective, the timescale of the generation deficit, i.e. when generation is less than load, plays a crucial role in determining the required storage timescale, and consequently, the type of storage technology. Generation and load variations occur over different timescales, including seconds (instantaneous balancing), hours (intra-day fluctuations), days (daily peaks and troughs), and even seasonally (long-term shifts in supply and demand). Given these diverse timescales, relying on a single storage solution may not be sufficient. Instead, an optimal solution is likely to involve a combination of storage modalities tailored to meet various deficit scenarios. For instance, short-term fluctuations may be handled by technologies like flywheel storage or Li-ion battery storage, which offer high power output and quick response times. In contrast, longer-term energy deficits, such as those that arise seasonally, may be better addressed by technologies like VFRBs or hydrogen storage, which provide large energy capacity over extended periods. However, such an analysis requires a complex holistic approach that considers each aspect (cost, timescales, etc.) of various storage technologies, and is beyond the scope of this current study.

An essential factor influencing the trajectory of Ireland's energy supply system is the policy framework that shapes the development of renewable energy technologies. Ireland's Offshore Renewable Energy Development Plan (OREDP) [51] acknowledges the country's ocean energy potential, including offshore wind, wave, and tidal energy. However, both the OREDP and the recent OREDP II [52], focus significantly on offshore wind, with wave energy still being viewed more as a 'potential resource' rather than a central component of future energy planning. In addition, Climate Action Plan 2024 [53], which is a 'roadmap of actions', classifies wave energy primarily under the domain of research and innovation rather than incorporating it as an immediate or concrete part of the energy mix. This classification reflects a cautious approach, where wave energy is seen as a potential but still developing technology. On the other hand, the EU have a more optimistic view of wave and tidal energy, with the objective for ocean energy to have at least 1 [GW] of installed capacity by 2030 and 40 [GW] by 2050 [54]. Moreover, as shown in this analysis, wave and tidal energy can play a crucial role in complementing wind and solar generation by filling in gaps during periods of low wind or sunlight, ultimately reducing the need for costly balancing storage. Yet, without supportive policies and incentives for research, development, and commercialisation of new technologies like wave energy, the potential benefits identified in this analysis may seem speculative and uncertain. Therefore, a supportive policy framework and continuous research and development could potentially make an impact in making new technologies, such as wave and tidal energy, commercially viable, which, as shown in this paper, can provide additional value to the supply system.

6. Conclusions

This paper explores the added value of combined renewable resource exploitation for the IoI, focusing on complementarity and balancing storage requirements. The complementarity assessment shows that increasing resource diversity enhances the overall complementarity, suggesting that incorporating additional diverse sources, such as wave and tidal energy, into the wind-solar mix could potentially benefit the Irish energy system. Complementarity is particularly strong in the north-east and south-east regions of the IoI, where high solar resources coincide with lower wind and wave resources during the summer months. Furthermore, the analysis highlights the challenges in accurately quantifying complementarity, with the total variation complementarity index, Φ, proving to be more effective than Φ_s and $\hat{\Phi}$, since Φ_s and $\hat{\Phi}$ tend to be more sensitive to data variations.

As Ireland transitions towards 100% renewable energy, optimising the resource mix and balancing storage requirements becomes vital. In a scenario aiming for 100% renewable energy, increasing wind capacity beyond a threshold of 7.65 [GW] requires significantly more storage, underscoring the need for a carefully balanced combination of energy sources to minimise storage requirements. Furthermore, a mix of all four RESs, i.e. wind, solar, wave, and tidal, leads to the lowest storage requirements, reinforcing the finding that a more diverse energy system provides greater complementarity. In transitional scenarios, the presence of fossil-fuel generation reduces the need for storage, but once fossil-fuel capacity falls below 100 [MW], storage requirements increase exponentially. This suggests that maintaining a small amount of dispatchable fossil-fuel capacity (50–100 [MW]) in the generation mix could be beneficial during the transition to a fully renewable system.

A techno-economic feasibility analysis of various storage modalities reveals that, while H_2 storage does not have the highest LCoS, it is not the most suitable option, due to its low turn-around efficiency. As a result, H_2 storage requires a significantly larger capacity compared to other alternatives. However, H_2 generation may provide additional benefits in industry and transport sectors [55]. Additionally, although PHS offers the lowest cost, its large physical footprint and specific topographical requirements make it impractical for large-scale implementation on the IoI. Since an electric grid requires both short- and long-term storage, a combination of multiple storage technologies, suitable for different scenarios, will be an appropriate solution. However, the mechanism by which this hybrid storage solution is effectively achieved requires further research.

Looking ahead, the techno-economic evolution of RESs and evolution of future load demand will likely impact these findings, with further analysis needed to account for uncertainties related to the use of reanalysis data. Future research should conduct detailed cost-benefit analyses of hybrid storage configurations, incorporating capital costs, efficiency losses, parameter uncertainty, and operational constraints to identify the most economically viable solutions. Another key research direction is the integration of detailed grid modelling to assess the impact of RES integration on grid stability, transmission constraints, and the role of flexibility measures, such as demand-side response, smart grid technologies, and interconnections, in complementing storage needs while accounting for grid connection and infrastructure limitations. Given the potential of hydrogen as a long-term energy storage solution, future studies should also explore hydrogen integration within Ireland's energy system, considering interactions with the power, transport, and industry sectors. In addition, it is worth noting that the potential benefits of integrating new technologies will only be realised if they receive adequate financial and policy support to reach commercial viability.

CRediT authorship contribution statement

Hafiz Ahsan Said: Writing – review & editing, Writing – original draft, Visualization, Investigation, Conceptualization. **Agustina Skiarski:** Writing – review & editing, Writing – original draft, Visualization, Investigation. **John V. Ringwood:** Writing – review & editing, Writing – original draft, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Spatial complementarity plots

See Figs. A.12–A.14.

Data availability

Data will be made available on request.

References

[1] EU. Renewable energy directive — energy.ec.europa.eu. 2024, https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en. [Accessed 29 May 2024].

[2] Ireland's National Energy and Climate Plan 2021–2030. Tech. rep., Department of the Environment, Climate and Communications; 2020.

[3] Renewables 2023: Analysis and forecast to 2028. Tech. rep., International Energy Agency; 2023.

[4] International Energy Agency. Energy system of Ireland. 2024, https://www.iea.org/countries/ireland. [Accessed 03 September 2024].

[5] Wind Energy Ireland. New record set for wind power generation in 2023. 2024, https://windenergyireland.com/latest-news/7651-new-record-set-for-wind-power-generation-in-2023#:~:text=Wind%20Energy%20Ireland%20confirmed%20that,gigawatt%2Dhours%20(GWh). [Accessed 30 July 2024].

[6] Shortt R. Amber alert over supply for electricity system lifted — rte.ie. 2024, https://www.rte.ie/news/2023/0612/1388720-amber-alert-electricity/. [Accessed 29 May 2024].

[7] Taveira-Pinto F, Rosa-Santos P, Fazeres-Ferradosa T. Marine renewable energy. Renew Energy 2020;150:1160–4.

[8] International Energy Agency. Energy technology perspectives 2020 – special report on clean energy innovation. 2024, https://www.iea.org/reports/energy-technology-perspectives-2020/clean-energy-innovation. [Accessed 29 May 2024].

[9] Fusco F, Nolan G, Ringwood JV. Variability reduction through optimal combination of wind/wave resources – An Irish case study. Energy 2010;35(1):314–25. http://dx.doi.org/10.1016/j.energy.2009.09.023.

[10] Said HA, Costello S, Ringwood J. On the complementarity of wave, tidal, wind and solar resources in Ireland. In: Proceedings of the European wave and tidal energy conference, vol. 15, 2023, p. 340/1–6.

[11] Electricity 2024: Analysis and forecast to 2026. Tech. rep., International Energy Agency; 2024.

[12] Connolly D, Lund H, Mathiesen BV, Leahy M. The first step towards a 100% renewable energy-system for Ireland. Appl Energy 2011;88(2):502–7.

[13] Connolly D, Mathiesen BV. A technical and economic analysis of one potential pathway to a 100% renewable energy system. Int J Sustain Energy Plan Manag 2014;1:7–28.

[14] Yue X, Patankar N, Decarolis J, Chiodi A, Rogan F, Deane J, et al. Least cost energy system pathways towards 100% renewable energy in Ireland by 2050. Energy 2020;207:118264.

[15] Becker S, Frew BA, Andresen GB, Jacobson MZ, Schramm S, Greiner M. Renewable build-up pathways for the US: Generation costs are not system costs. Energy 2015;81:437–45.

[16] Bogdanov D, Breyer C. North-East Asian Super Grid for 100% renewable energy supply: Optimal mix of energy technologies for electricity, gas and heat supply options. Energy Convers Manage 2016;112:176–90.

[17] Heide D, von Bremen L, Greiner M, Hoffmann C, Speckmann M, Bofinger S. Seasonal optimal mix of wind and solar power in a future, highly renewable Europe. Renew Energy 2010;35(11):2483–9. http://dx.doi.org/10.1016/j.renene.2010.03.012.

[18] Elliston B, MacGill I, Diesendorf M. Least cost 100% renewable electricity scenarios in the Australian National Electricity Market. Energy Policy 2013;59:270–82. http://dx.doi.org/10.1016/j.enpol.2013.03.038.

[19] Hansen K, Breyer C, Lund H. Status and perspectives on 100% renewable energy systems. Energy 2019;175:471–80. http://dx.doi.org/10.1016/j.energy.2019.03.092.

[20] Narayanan A, Mets K, Strobbe M, Develder C. Feasibility of 100% renewable energy-based electricity production for cities with storage and flexibility. Renew Energy 2019;134:698–709. http://dx.doi.org/10.1016/j.renene.2018.11.049.

[21] Pennock S, Coles D, Angeloudis A, Bhattacharya S, Jeffrey H. Temporal complementarity of marine renewables with wind and solar generation: Implications for GB system benefits. Appl Energy 2022;319:119276. http://dx.doi.org/10.1016/j.apenergy.2022.119276.

[22] Heide D, Greiner M, von Bremen L, Hoffmann C. Reduced storage and balancing needs in a fully renewable European power system with excess wind and solar power generation. Renew Energy 2011;36(9):2515–23. http://dx.doi.org/10.1016/j.renene.2011.02.009.

[23] François B, Hingray B, Raynaud D, Borga M, Creutin J. Increasing climate-related-energy penetration by integrating run-of-the river hydropower to wind/solar mix. Renew Energy 2016;87:686–96. http://dx.doi.org/10.1016/j.renene.2015.10.064.

[24] François B, Borga M, Creutin JD, Hingray B, Raynaud D, Sauterleute JF. Complementarity between solar and hydro power: Sensitivity study to climate characteristics in Northern-Italy. Renew Energy 2016;86:543–53. http://dx.doi.org/10.1016/j.renene.2015.08.044.

[25] François B, Zoccatelli D, Borga M. Assessing small hydro/solar power complementarity in ungauged mountainous areas: A crash test study for hydrological prediction methods. Energy 2017;127:716–29. http://dx.doi.org/10.1016/j.energy.2017.03.090.

[26] Bhattacharya S, Pennock S, Robertson B, Hanif S, Alam MJE, Bhatnagar D, et al. Timing value of marine renewable energy resources for potential grid applications. Appl Energy 2021;299:117281. http://dx.doi.org/10.1016/j.apenergy.2021.117281.

[27] Gao Q, Yuan R, Ertugrul N, Ding B, Hayward JA, Li Y. Analysis of energy variability and costs for offshore wind and hybrid power unit with equivalent energy storage system. Appl Energy 2023;342:121192. http://dx.doi.org/10.1016/j.apenergy.2023.121192.

[28] Gao Q, Bechlenberg A, Jayawardhana B, Ertugrul N, Vakis AI, Ding B. Techno-economic assessment of offshore wind and hybrid wind–wave farms with energy storage systems. Renew Sustain Energy Rev 2024;192:114263. http://dx.doi.org/10.1016/j.rser.2023.114263.

[29] ERA5 hourly data on single levels from 1940 to present. 2024, https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels. [Accessed 06 February 2024].

[30] Marine Data Center, Marine Institute. 2024, https://www.marine.ie/site-area/data-services/marine-data-centre. [Accessed 06 February 2024].

[31] SEAI. Tidal & current energy resources in Ireland. Tech. rep., Sustainable Energy Authority Ireland; 2011, https://www.seai.ie/publications/Tidal_Current_Energy_Resources_in_Ireland_Report.pdf.

[32] Entsoe Transparency Platform. 2024, https://transparency.entsoe.eu/load-domain/r2/totalLoadR2/show. [Accessed 06 February 2024].

[33] EirGrid, SONI. All-Island generation capacity statement 2022–2031. Tech. rep., EirGrid and SONI; 2022.

[34] Dalton G, Alcorn R, Lewis T. Case study feasibility analysis of the Pelamis wave energy convertor in Ireland, Portugal and North America. Renew Energy 2010;35(2):443–55. http://dx.doi.org/10.1016/j.renene.2009.07.003.

[35] Mérigaud A, Ringwood JV. Power production assessment for wave energy converters: Overcoming the perils of the power matrix. Proc Inst Mech Eng Part M: J Eng Marit Environ 2018;232(1):50–70. http://dx.doi.org/10.1177/1475090217731671.

[36] W2E wind to energy W2E-215/9.0. 2023, https://en.wind-turbine-models.com/manufacturers/314-w2e-wind-to-energy. [Accessed 16 May 2023].

[37] Perpiñan O, Lorenzo E, Castro MA. On the calculation of energy produced by a PV grid-connected system. Prog Photovolt, Res Appl 2007;15(3):265–74. http://dx.doi.org/10.1002/pip.728.

[38] Zhang Y, Campana PE, Lundblad A, Wang L, Yan J. The influence of photovoltaic models and battery models in system simulation and optimization. Energy Procedia 2017;105:1184–91. http://dx.doi.org/10.1016/j.egypro.2017.03.409.

[39] JAM72S30 525-550 MR, Shanghai JA Solar Technology Co Ltd.. 2023, https://www.jasolar.com/uploadfile/2021/0706/20210706053524693.pdf. [Accessed 16 May 2023].

[40] Cantor D, Ochoa A, Mesa O. Total variation-based metrics for assessing complementarity in energy resources time series. Sustainability 2022;14(14):8514. http://dx.doi.org/10.3390/su14148514.

[41] Mohammadi SS, Brennan M, Oberoi A, Vagh H, Spencer M, Kumar TD, et al. Density functional theory and ab initio molecular dynamics investigation of hydronium interactions with graphene. Energy Procedia 2017;110:518–22. http://dx.doi.org/10.1016/j.egypro.2017.03.178.

[42] Zakeri B, Syri S. Electrical energy storage systems: A comparative life cycle cost analysis. Renew Sustain Energy Rev 2015;42:569–96. http://dx.doi.org/10.1016/j.rser.2014.10.011.

[43] Smallbone A, Jülch V, Wardle R, Roskilly AP. Levelised cost of storage for pumped heat energy storage in comparison with other energy storage technologies. Energy Convers Manage 2017;152:221–8. http://dx.doi.org/10.1016/j.enconman.2017.09.047.

[44] Jülch V. Comparison of electricity storage options using levelized cost of storage (LCOS) method. Appl Energy 2016;183:1594–606. http://dx.doi.org/10.1016/j.apenergy.2016.08.165.

[45] Mugyema M, Botha C, Kamper M, Wang R-J, Sebitosi A. Levelised cost of storage comparison of energy storage systems for use in primary response application. J Energy Storage 2023;59:106573. http://dx.doi.org/10.1016/j.est.2022.106573.

[46] Züttel A. Hydrogen storage methods. Naturwissenschaften 2004;91:157–72. http://dx.doi.org/10.1007/s00114-004-0516-x.

[47] Coburn A, Walsh E, Solan PJ, McDonnell KP. Combining wind and pumped hydro energy storage for renewable energy generation in Ireland. J Wind Energy 2014;2014(1):415898. http://dx.doi.org/10.1155/2014/415898.

[48] Gür TM. Review of electrical energy storage technologies, materials and systems: challenges and prospects for large-scale grid storage. Energy & Environ Sci 2018;11(10):2696–767. http://dx.doi.org/10.1039/C8EE01419A.

[49] Hoare P. Seven ‘amber alerts’ on national electricity grid spark supply fears. 2024, https://www.irishexaminer.com/news/arid-40745073.html. [Accessed 09 September 2024].

[50] European Comission. SET Plan information system – Ocean energy. 2024, https://setis.ec.europa.eu/implementing-actions/ocean-energy_en. [Accessed 27 August 2024].

[51] Department of the Environment, Climate and Communications. Offshore Renewable Energy Development Plan (OREDP). 2021, https://www.gov.ie/en/publication/e13f49-offshore-renewable-energy-development-plan/. [Accessed 09 September 2024].

[52] Department of the Environment, Climate and Communications. Offshore Renewable Energy Development Plan II (OREDP II). 2023, https://www.gov.ie/en/publication/71e36-offshore-renewable-energy-development-plan-ii-oredp-ii/. [Accessed 02 October 2024].

[53] Department of the Environment, Climate and Communications. Climate Action Plan 2024. 2024, https://www.gov.ie/en/publication/79659-climate-action-plan-2024/.[Accessed 09 September 2024].

[54] European Commission. Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions: Delivering on the EU offshore renewable energy ambitions. 2023, p. 1–20, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52023DC0668. [Accessed 25 September 2024].

[55] Oliveira AM, Beswick RR, Yan Y. A green hydrogen economy for a renewable energy society. Curr Opin Chem Eng 2021;33:100701. http://dx.doi.org/10.1016/j.coche.2021.100701.