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Enhancing Islanded Power Systems: Microgrid Modeling and Evaluating System Benefits of Ocean Renewable Energy Integration

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Abstract: The energy transition hinges on the effective integration of renewable energy sources into the power grid. Islands can provide invaluable insights into the challenges and opportunities of integrating variable renewable energy into the grid due to their relatively small power systems, isolated grids, and diverse availability of renewable energy resources. This paper presents a study on the system benefits and challenges of marine energy integration in insular power systems, focusing on the Orkney Islands as a case study. A microgrid modeling approach that optimizes the mix of renewable sources and energy storage systems for future scenarios considering strategic time horizons (2030, 2040, and 2050) was employed. Results suggest that integrating ocean energies, namely, wave and tidal energy, yields notable benefits compared to traditional renewable energy sources exclusively. These benefits encompass reduced installed capacity, minimized energy storage requirements, lower excess generation, and overall cost-saving.

Keywords: islanded power systems; ocean energy integration; microgrid modeling

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1. Introduction

In the last few years, the European Commission has been committed to the energy transition through the deployment of endogenous renewable energy sources, both as a measure to reduce carbon emissions and also as a vital strategy to ensure long-term energy security. The war situation in Ukraine, which triggered a widespread energy crisis across Europe, has amplified this engagement.

Despite the accelerated deployment of renewable energy in Europe in the last two decades, which increased the share of renewables in electricity generation from 15.9% in 2004 to 39.4% in 2022, the current installed renewable capacity still falls short of meeting total energy demands [1]. This shortfall underscores the need to further expand and diversify the portfolio of renewable energy, namely, by tapping into marine energy sources, and developing new technologies and strategies to mitigate the challenges related to grid integration.

Islanded power systems present a unique opportunity for the study of renewable energy integration. Islands tend to present abundant and diverse renewable energy resources, namely, solar (particularly in tropical locations), wind, and also wave and tidal [2]. Their inherent isolation from larger grids makes them reliant on local energy resources, often leading to high electricity costs and dependence on imported fossil fuels. This makes them prime candidates for renewable energy widespread adoption, as integrating sustainable sources can lead to significant cost-saving, enhanced energy security, and reduced carbon emissions [3]. Finally, their small scale and limited interconnections with the mainland render islands ideal laboratories for studying the challenges arising from the high penetration of renewable energy in the grid, providing valuable insights into grid stability, energy storage solutions, and demand-side management strategies, and also the integration of ocean energy technologies such as wave and tidal.

Fixed offshore wind is a well-established, leading technology, boasting a total 30.3 GW of total installed capacity across Europe in 2022 [2]. Albeit being less developed than offshore wind, wave and tidal are clean, abundant, powerful, and, thus, very relevant sources of renewable energy. These technologies still must overcome hurdles related to performance, reliability, and survivability, which currently result in costs exceeding grid parity [4]. However, particularly for islanded power systems, ocean energy can offer significant advantages to the grid. They have low variability when compared to wind, can be more accurately forecasted, and are fit to respond to the electricity demand during night-time periods. Their generation profile is complementary to wind and solar renewable energy outputs, matching loads, decreasing energy storage needs, and potentially lowering costs [5].

To date, several studies have been conducted on islanded power systems, mostly dedicated to specific locations, such as the case of Maldives [6] or in the Canary Islands [7], or as in [8], seeking to classify islands by their potential to explore some renewable sources. However, these studies do not include wave and tidal. The deployment of marine energy technologies, such as wave and tidal, in islands, has been studied extensively [9–11]. These studies focused on demonstrating the potential of integrating these specific marine renewable energy systems into islanded contexts. Keiner et al. [12] studied how to leverage a mix of floating solar PV, offshore wind, and wave energy for powering island energy systems with 100% renewables, focusing on the Maldives as a case study, while Neto et al. [13] studied the complementarity between tidal, solar, and wind to supply an island in the north of Brazil. However, the holistic study of islanded power systems, considering their marine renewable energy resources, remains vastly underexplored with respect to the potential benefits in terms of costs, total installed capacity, energy storage needs, and grid stability.

In this context, the project EVOLVE—“Economic value of ocean energy”, funded by the EC’s OCEANERA-NET program, sought, generally speaking, to identify and quantify the benefits of integrating ocean energies in the electrical system, assessing different regional scales, such as the case of islanded grids [14]. The present paper aims to address this research gap by developing a comprehensive microgrid modeling assessment of an islanded power system, to quantify the potential benefits of integrating marine renewable energy into the power grid. Given its abundant and diverse renewable energy resource, extensive data availability, and its strong bet in marine renewable energy development, the Orkney Islands were selected as the case study presented in this paper. A dual simplex linear optimization algorithm was developed to model various scenarios, considering different electricity demand conditions and outputting cost-optimal energy system solutions that incorporate different renewable energy portfolios, providing means to assess the integration of wave and tidal energies compared with having only offshore wind, solar PV, onshore and offshore wind, and an alternative case of electricity import. Two energy storage technologies are considered, namely, lithium-ion batteries and hydrogen storage. The model is based on hourly data regarding renewable energies resources and the consumption, which brings a degree of uncertainty to the analysis, since estimations of the future demand are required. There is also some uncertainty with respect to the cost projection for the future commissioning years (2030, 2040, and 2050). It should be noted that results obtained are location-dependent, given the specific available resources and consumption profiles. Nevertheless, the main conclusions should be transversal to other islands with approximately similar marine renewables resources. Moreover, the tool developed to conduct the present study may be easily adapted to different renewables contents and consumption characteristics. In the context of the EVOLVE project, it is another work focused on studying the integration of wave and tidal energies on Great Britain’s grid [15]. Though both present different methodology and metrics, the two works fit complementarily in the goals of the project in terms of spatial scales, and the main outcomes are similar with respect to the benefits of including wave and tidal in the energy system. In Section 2, the dual simplex linear optimization methodology is presented. Section 3 presents the Orkney Islands case study, covering the electricity demand assumptions and technology costs. The results of the assessment are presented in Section 4 for two scenarios: closed grid and open grid. The most important outcomes of the work are compiled in Section 5.

2. Methodology

A linear programming algorithm was implemented with the aim of optimizing the combination of installed capacity for renewable energy sources and the corresponding complementary energy storage systems to meet a specified consumption profile. The approach follows the well-known dual-simplex algorithm described in [16], which was also applied in a previous study concerning a renewable energy-supplied island desalination facility [2]. The linear programming challenge at hand revolves around minimizing the cost function defined in Equation (1):

$$f_{cost}(x) = \boldsymbol{c} \cdot \boldsymbol{x}, \tag{1}$$

Here, $\boldsymbol{x}$ represents an N-by-1 vector containing the variables under optimization, that is, the generation-installed power capacity of each of the various renewable energy types under examination (measured in MW). Furthermore, in consideration of improved energy surplus management, the variable vector for optimization is extended to encompass energy storage capacity (measured in MWh). Additionally, it includes the temporal energy input and output series into and from the storage plant. For grids that are not isolated and allow for electricity imports/exports, two additional vectors related to the import and export electricity flow must be added. $\boldsymbol{c}$ denotes a 1-by-N vector comprising the costs associated with each respective variable. More specifically, it represents the cost per MW of installed capacity for the generation technologies and the cost per MWh in the case of the storage plants. For each generation technology, the cost is given by:

$$c_{gen\ per\ MW} = CapEX_{per\ MW} + OpEX_{per\ MW\ per\ year} * lifetime$$

where $c_{gen\ per\ MW}$ is the capital expenditures per MW of installed power capacity, $OpEX_{per\ MW\ per\ year}$ corresponds to the operational expenditures per MW of installed capacity and per year of operation, and lifetime is the total number of years of the operating plant. As a simplification, all technologies are assumed to have a lifetime of 25 years. N signifies the number of variables. The variables targeted for optimization may be subject to constraints, which can be expressed as a set of inequalities in Equation (2),

$$\boldsymbol{A}\,\boldsymbol{x} \le \boldsymbol{b}, \tag{2}$$

or by a set of equalities, as in Equation (3):

$$\boldsymbol{A_{eq}}\,\boldsymbol{x} = \boldsymbol{b_{eq}}. \tag{3}$$

In this context, $\boldsymbol{A}$ corresponds to an M-by-N matrix, while $\boldsymbol{b}$ denotes an M-by-1 vector, with M representing the total number of inequality constraints. Similarly, $\boldsymbol{A_{eq}}$ denotes an M_{eq}-by-N matrix, and $\boldsymbol{b_{eq}}$ signifies an M_{eq}-by-1 vector, where M_{eq} stands for the number of equalities. An example is presented below to clarify these parameters.

Figure 1 provides a schematic representation of the model, illustrating its inputs, outputs, and the interconnected variables.

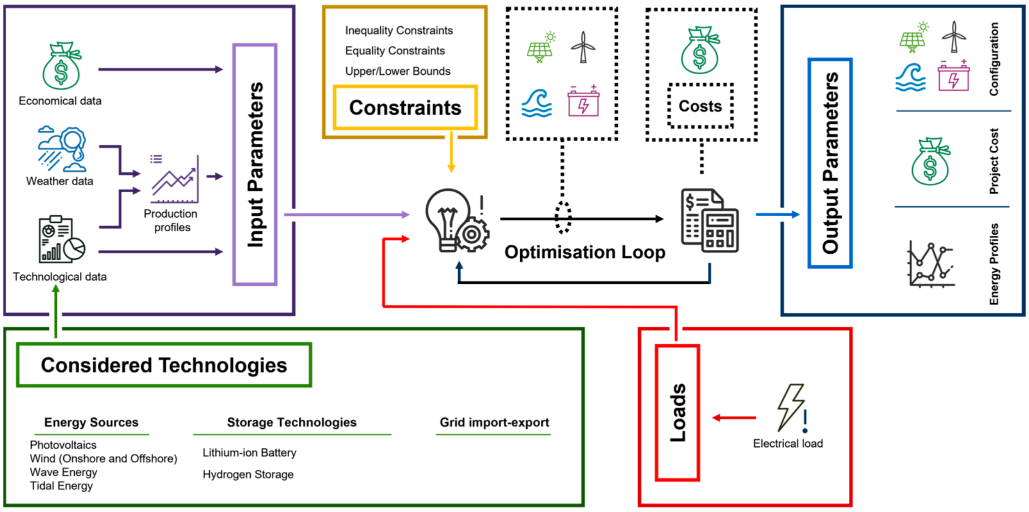

Figure 1. Schematic diagram of the renewable energy installed capacity optimization model.

Ultimately, the list of inputs of the model include (i) time series for electricity consumption, (ii) time series of technology-specific generation for each installed MW, (iii) CAPEX and OPEX figures per MW for various electricity generation technologies and storage facilities, (iv) storage parameters such as round-trip efficiency, depth of discharge, and the ratio between energy storage capacity and power output, and (v) transmission cable constraints that limit electricity imports/exports (set to zero when the grid is isolated).

The outputs yielded by the model include the optimal installed capacity for each electricity generation and storage technology, time series of electricity generation by technology and electricity storage flows, the resulting costs, and the surplus of electricity production or curtailment. For instance, considering a scenario that involves ocean-based renewable technologies, exclusively hydrogen as the chosen energy storage system, and the absence of transmission connections between a given island and mainland, the variables pertinent to the problem are as follows:

$$\boldsymbol{x} = \left[x_{ow},\ x_{wave}, x_{tidal},\ x_{H2cap}, \boldsymbol{x_{H2in}}, \boldsymbol{x_{H2out}}\ \right], \tag{4}$$

where x_{ow}, x_{wave} and x_{tidal} are scalars that represent the installed capacity (in MW) of offshore wind (fixed), wave, and tidal energy sources, respectively. Additionally, x_{H2cap} is a scalar that corresponds to the maximum hydrogen storage capacity (in MWh), while $\boldsymbol{x_{H2in}}$ and $\boldsymbol{x_{H2out}}$ are two N-by-1 vectors that refer to the time series detailing the input and output of electricity into and from the hydrogen storage infrastructure (in MWh).

The matrix A within the inequalities system (Equation (2)) is constructed by utilizing electricity production profiles per MW of installed capacity for each technology, employing year-long time series data, and incorporating relevant parameters associated with the storage system (such as round-trip efficiency and depth of discharge). Simultaneously, the vector b within the same inequalities system encompasses a year-long time series outlining the electricity consumption pattern. In order to clarify parameters A and b, subsets are represented below, which correspond to imposing that the electricity generation and the contribution from the storage satisfy the consumption.

$$\boldsymbol{A_{sub}} = \left[-\boldsymbol{gen_{offwind}}, -\boldsymbol{gen_{waves}}, -\boldsymbol{gen_{tidal}},\ \boldsymbol{z},\ \boldsymbol{I}, -\boldsymbol{I}\ *\ \eta_{H2}\right]$$

where the parameters gen are column vectors representing the time series of the electricity generation per MW of installed capacity, z is a zero-column vector with the same length of gen, $\boldsymbol{I}$ is the identity matrix with the same size, and η_{H2} is the round-trip efficiency of the H2 plants. The right-hand side of the inequality is:

$$\boldsymbol{B_{sub}} = -\boldsymbol{dem}$$

where ***dem*** is a column vector comprehending the electricity demand time series. Other subsets are implemented to account for the energy power output and energy capacity, which should be equal to or higher than the state of charge. For the sake of clarity, Figure 2 depicts a set of time series regarding a short period of time (5 days), representing the consumption, the generation from the renewables and its total, and the electricity flow into and out from the storage equipment. This is the model's result for 2040 as the commissioning year, considering all renewable sources (different sets of renewables are object of this study). Note that solar PV (in yellow) and tidal (dark blue) present very low contributions, and onshore wind does not have any installed capacity in this particular solution. It is possible to identify that in intervals of time, the total generation is higher than the demand, presenting a negative storage flow, which means that the equipment is storing energy. For the other way around, when the total generation from renewables is lower than the consumption, the storage flow is positive, contributing to cover the demand.

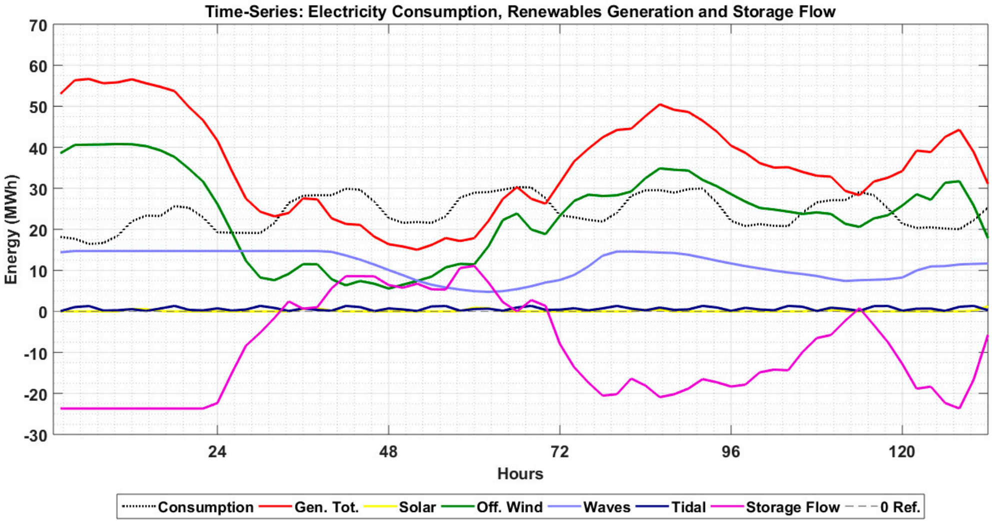

Figure 2. Five-day time series of consumption, generation, and storage flow resultant from the model.

To assess potential cost reductions from integrating ocean renewable energies in the power system, the optimization model is applied to a variety of scenarios comprising different renewable sources. These scenarios are identified in Table 1. Note that in this study offshore wind refers to fixed turbines.

Table 1. Explanation of the renewable sources assumed for each of the tested scenarios.

Scenario	Renewable Energy Sources Considered
Land	Onshore wind and solar PV
Offshore renewables	Waves, tidal and offshore wind
Offshore wind	Only offshore wind
All	All five sources

3. The Case of the Orkney Islands

For the purpose of assessing the potential advantages of integrating electricity from oceanic renewable sources into the power grid, analyzing an isolated islanded electrical system can provide valuable insights. The Orkney Islands, with their relatively small scale and abundant renewable resources, stand out as an ideal case study. This section presents the most relevant inputs for the study, such as the local electricity consumption, the generation from the considered renewable technologies, and costs related to different generation and storage technologies, amongst other parameters and assumptions.

3.1. Electricity Demand

For the purpose of optimizing the island electricity grid, a fundamental input encompasses a time series that represents the electricity demand in Orkney. In this study, Orkney Islands' electricity demand time series were obtained by appropriately scaling historical data encompassing the entirety of Great Britain (GB) for the year of 2019 [17]. The scaling factor was calculated as the ratio between the total electricity consumption in Orkney and in Great Britain, for the same year. These data were obtained from the national electricity consumption statistics published in [17].

Figure 3a illustrates the monthly distribution pattern of electricity power demand considered in the model for Orkney. Notably, the average power demand exhibits an upswing during the colder months, coupled with a shorter duration of daylight (from October to March). Figure 3b delves deeper into this narrative by presenting detailed information, portraying the averaged power consumption spanning various times of the day for each month. On average, within the early hours of 0–6 a.m., the electricity consumption remains notably minimal across all months due to reduced human activity during this period. For the rest of the day, consumption patterns show some consistency during colder months: 12–18 h sees a slight uptick in consumption, while the 18–24 h window shows a modest reduction. These daily fluctuations are slightly less pronounced in the summer months.

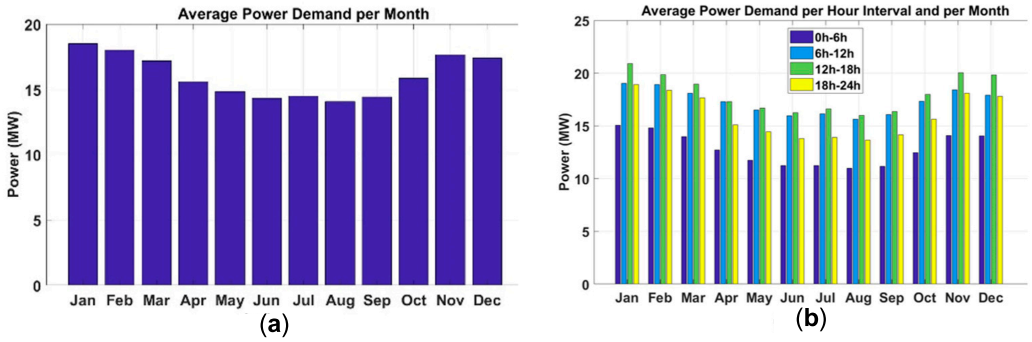

Figure 3. On the left: Orkney Islands' monthly averaged power demand (**a**); on the right: Orkney Islands' power demand distribution per period of the day for each month (**b**).

Given the speed-up of the electrification process in order to meet the decarbonization targets across GB and continental Europe, the electricity consumption in the Orkney Islands is expected to increase in the next years. Hence, three different future consumption scenarios were considered, for 2030, 2040, and 2050. These future scenarios, presented in Figure 4 as a factor that multiplies by the demand profile of 2019, were based on a study developed within the project EVOLVE [18], which relies on the report by the National Grid ESO [17]. The decrease in the consumption shown in the beginning of the plot is a trend that, in accordance with the national grid report, has been verified since 2011. The referred study from EVOLVE includes some considerations with respect to demand flexibility from residential heating and smart charging, but flexibility from industrial and commercial demand is not accounted for, nor is vehicle to grid management.

3.2. Renewable Electricity Generation Assumptions

The distinct attributes characterizing diverse renewable energy technologies for electricity generation serve as fundamental inputs to the model. The considered renewable energy sources encompass solar photovoltaic (PV), onshore wind, offshore wind, wave, and tidal stream. Each renewable energy technology entails a one-year profile of electricity generation per MW of installed capacity, featuring hourly data. These time series originate from energy resource assessments for Orkney and the application of technology-specific models. This dataset was acquired through the OCEANERA-NET EVOLVE Project [18] from different sources:

- Solar PV: Renewables Ninja [19] utilizing coordinates: 58.9182, −2.8931, tilt: 35 degrees, azimuth: 180 degrees.
- Onshore wind: Renewables Ninja [19] utilizing coordinates: 59.1012, −3.0984, with a reference Vestas V90 2 MW turbine.
- Offshore wind: Renewables Ninja [19] utilizing coordinates: 58.7647, −2.2632, with a reference Vestas V164 9.5 MW turbine.
- Waves: Utilizing Copernicus' northwest shelf analysis for resource estimation and a wave power matrix from CorPower Ocean for a designated future device (G12).
- Tidal stream: Based on Thesis modeling by the University of Edinburgh and the University of Plymouth [20], located at Lashy Sound.
- Figure 5's bar chart illustrates the average electricity power generation per MW of installed capacity for solar PV, onshore wind, offshore wind, wave, and tidal energy over each month.

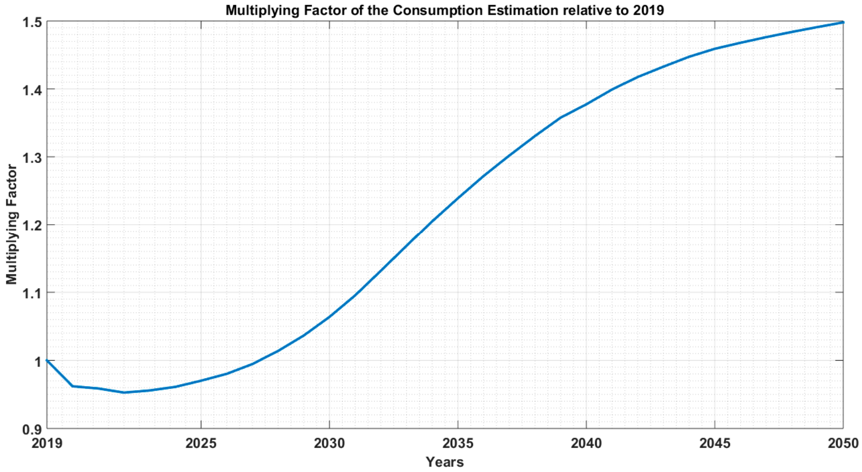

Figure 4. Factor projection for the future consumption in the Orkney Islands for the 2019–2050 period, with reference to 2019.

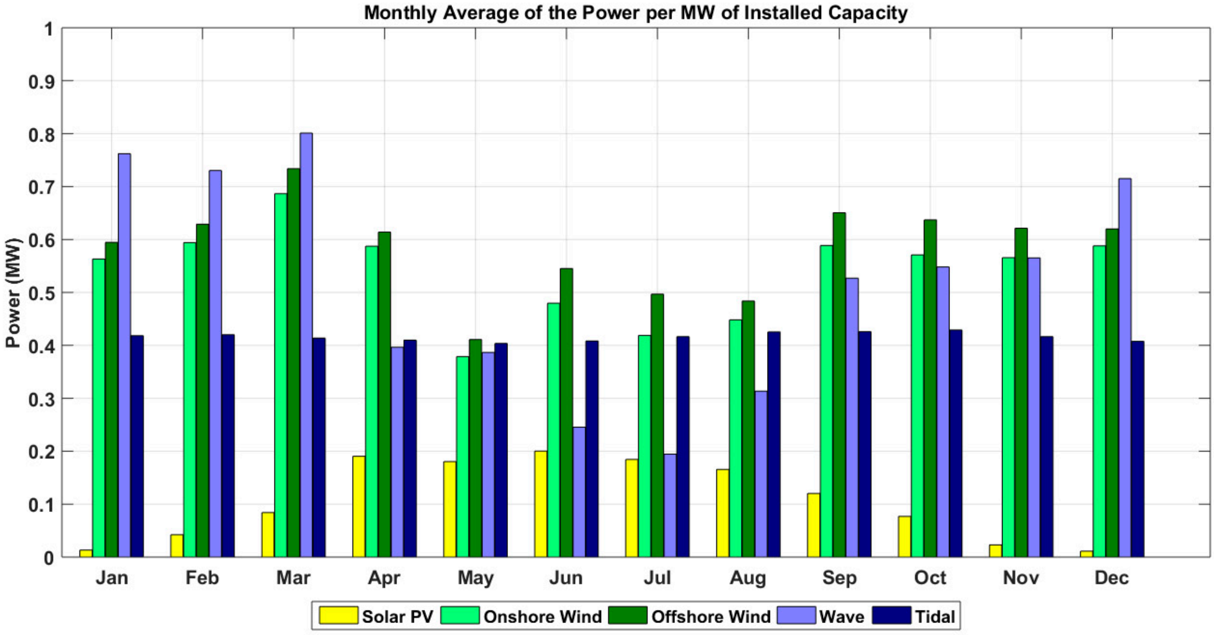

Figure 5. Monthly average of electricity power generation in Orkney for solar PV, onshore and offshore wind, wave, and tidal, per installed MW.

As expected, solar PV exhibits the lowest electricity generation among the sources, with almost negligible output between November and February. In the most productive months, the average generation per MW of installed capacity barely surpasses 200 kW. Tidal energy's generation remains relatively consistent throughout the year, fluctuating within the 400–430 kW range. Onshore and offshore wind present comparable monthly averages, spanning from nearly 400 kW to 700 kW, with lower generation observed during the summer months. Wave energy attains the highest monthly average, reaching approximately 830 kW, with peak averages from October to March at around 700 kW. During the same period, onshore and offshore wind exhibit averages close to 600 kW. Nevertheless, wave energy generation displays wider variation, with its lowest value at 220 kW in July.

3.3. Storage Characteristics and Transmission Capacity

In order to better manage some of the mismatch between the periods of higher electricity consumption and the generation from renewable sources, two types of energy storage are considered: lithium-ion batteries (LI) and hydrogen. Essentially, the model assumes that if for a time window there is an excess of electricity generation, it is either stored or curtailed. It is considered that stored hydrogen is exclusively used for later reconversion to electricity and is not to be used in any other form. Table 2 identifies basic characteristics of the energy storage equipment, such as the efficiency and the depth of discharge. The ratio of the energy storage capacity to the power output is also shown. The values are based on the BEIS's report for the storage cost projection [21]. This means that for lithium-ion batteries, equipment with 1 MW of power has an energy storage capacity of 1 MWh, whereas a hydrogen storage facility rated at 1 MW of power can store 250 MWh of energy.

Table 2. Characteristics of the energy storage equipment considered in the study.

Technology	Efficiency	Depth of Discharge	Energy Storage/Power
LI Batteries	90%	80%	1
Hydrogen	32%	100%	250

Presently, the Orkney Islands have two 33 kV subsea electrical cables that connect the islands to mainland with a total capacity of 40 MW, although further expansion of the transmission capacity is under development.

3.4. Generation and Storage Technology Costs

The future cost projections for different renewable electricity generation technologies were partially derived from the 2020 BEIS report [22]. Projections relating to wave and tidal energy costs were estimated by CorPower Ocean (CPO) and Orbital Marine Power (OMP), respectively. The BEIS report presents, for each technology, two alternative scenarios, low-cost and high-cost scenarios, which correspond to more optimistic and more pessimistic estimations, respectively, in order to account some uncertainties. Notably, the BEIS report lacks cost projections extending to 2050. For this reason, for this specific year of commissioning, costs were deduced by factoring in the projected evolution across the available years mentioned in the report (2025, 2030, 2035, and 2040). It is important to highlight that for each technology, a decrease rate lower than that of the preceding years is assumed. This effect is visually elucidated in Figure 6.

With regard to the energy storage systems, cost data are based on another report from BEIS [21]. Table 3 presents a summary of the electricity generation costs per MW of installed capacity. The costs of the energy storage systems are presented in Table 4.

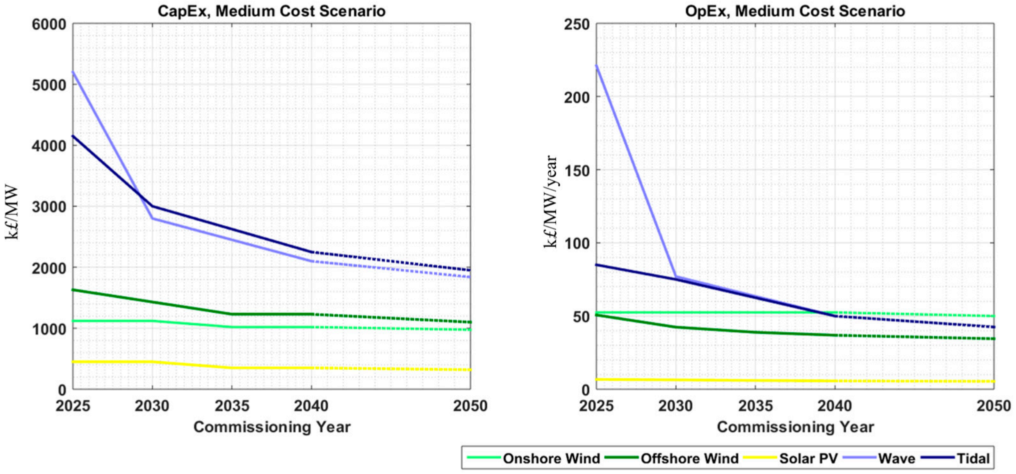

Figure 6. Electricity generation: CapEx and OpEx projections evolution and extrapolation to 2050.

Table 3. Summary of the electricity generation costs [22].

Technology	Commissioning Year	CAPEX kGBP/MW			OPEX kGBP/MW/year
		Low	Medium	High	
Onshore Wind	2030	940.0	1120.0	1300.0	52.5
	2040	840.0	1020.0	1200.0	52.5
	2050	810.0	975.0	1140.0	50.0
Offshore Wind	2030	1160.0	1430.0	1600.0	42.4
	2040	960.0	1230.0	1400.0	36.9
	2050	870.0	1100.0	1240.0	34.5
Solar PV	2030	310.0	450.0	520.0	6.4
	2040	210.0	350.0	420.0	5.7
	2050	190.0	320.0	370.0	5.4
Wave	2030	1680.0	2800.0	3890.0	77.0
	2040	1260.0	2100.0	2920.0	50.0
	2050	1100.0	1840.0	2580.0	42.5
Tidal	2030	1800.0	3000.0	4170.0	75.0
	2040	1350.0	2250.0	3128.0	50.0
	2050	1170.0	1950.0	2711.0	42.5

Table 4. Summary of the energy storage systems costs [21].

Technology	Commissioning Year	CAPEX GBP/kW			OPEX GBP/kW/year		
		Low	Medium	High	Low	Medium	High
LI Batteries	2030	241.0	292.4	348.0	2.5	4.4	6.1
	2040	192.3	233.9	279.7	2.0	3.5	4.8
	2050	166.8	203.4	244.1	1.7	3.0	4.2
Hydrogen	2030	789.1	876.8	964.5	19.7	21.9	24.1
	2040	735.4	817.1	898.9	18.3	20.3	22.3
	2050	703.5	781.7	859.9	17.4	19.3	21.3

4. Results and Discussion

The present section describes the outcomes from the present study. The model's primary objective is determining the cost-optimal mix of renewable sources and storage that meets electricity demand. A comprehensive set of simulations was conducted to cover a wide range of scenarios:

- Year of commissioning: 2030, 2040, and 2050, each wielding influence over cost projections.
- Cost scenarios: Low, medium, and high.

- Categories of renewable sources: Land-based, ocean-based, exclusively offshore wind, and a comprehensive assortment.

Simulations were carried out for different years, different cost scenarios (low, medium, high), and different combinations of renewable energy generation, in order to identify the optimal generation and storage capacity that minimize system costs. For each simulation, the model considers that the entirety of the generation capacity is installed and readily available to operate from day one; thus, no progressive installations are considered. Four different cases were simulated corresponding to different combinations of renewable energy technologies:

- Land-based (Land): Only considers land-based renewable energy, which includes solar PV and onshore wind.
- Offshore Renewable Energy (ORE): Only considers offshore wind, wave, and tidal.
- Offshore Wind (Off. Wind): Only considers offshore wind.
- All: Considers combinations of all renewable energy sources.

Two different grid configurations were also simulated: (i) closed-grid scenario, where no electrical connection to mainland exists, and (ii) open-grid scenario, where the electricity imports and exports from/to mainland are possible. The results are presented in the following two subsections.

4.1. Closed-Grid Scenario (No Import/Export Considered)

In this subsection, outcomes are presented under the premise of an isolated grid scenario, encompassing cost considerations for three distinct commissioning years. Additionally, a direct comparison among various categories of renewable sources included in the mix is performed. The term "closed grid" denotes a situation wherein all requisite electricity is exclusively generated through the assumed renewable energy technologies, without contributions from external sources. The model considers that any surplus of electricity generation is either stored and/or curtailed, depending on which is more cost-effective.

These results are derived from a medium-cost scenario projection. While there are minor deviations, the solutions for low- and high-cost scenarios mirror the same overarching concepts and trends as the medium-cost scenario. To prevent excessive duplication of figures conveying nearly identical information, outcomes for low- and high-cost scenarios are detailed in Appendix A. The ensuing graphs visually depict the solutions for the subsequent variables:

- Installed power capacity of renewable sources;
- Energy storage capacity;
- Excess of electricity generation, represented as a percentage of total demand;
- Global costs.

The mix of renewable sources for the medium-cost scenario is shown in Figure 7, having 2030, 2040, and 2050 as commissioning years. The most relevant conclusion across the three years is that the offshore renewable energies scenario presents a lower total installed capacity to satisfy the consumption. For each scenario, the total installed capacity increases, since the consumption grows, but land, all, and only offshore wind scenarios present 10% to 25% more than ORE. This suggests a good complementarity between offshore wind, tidal, and wave energy generation. It could be expected that the all-energies scenario would present the lowest total installed capacity, since it has more possibilities to find a solution with improved complementary generation. However, the model selects the mix that corresponds to a lower cost, and including solar PV lowers the global cost. Although it is not considered in this study, less total installed capacity might represent less use of material and a lower carbon footprint, but this needs to be confirmed with a dedicated analysis.

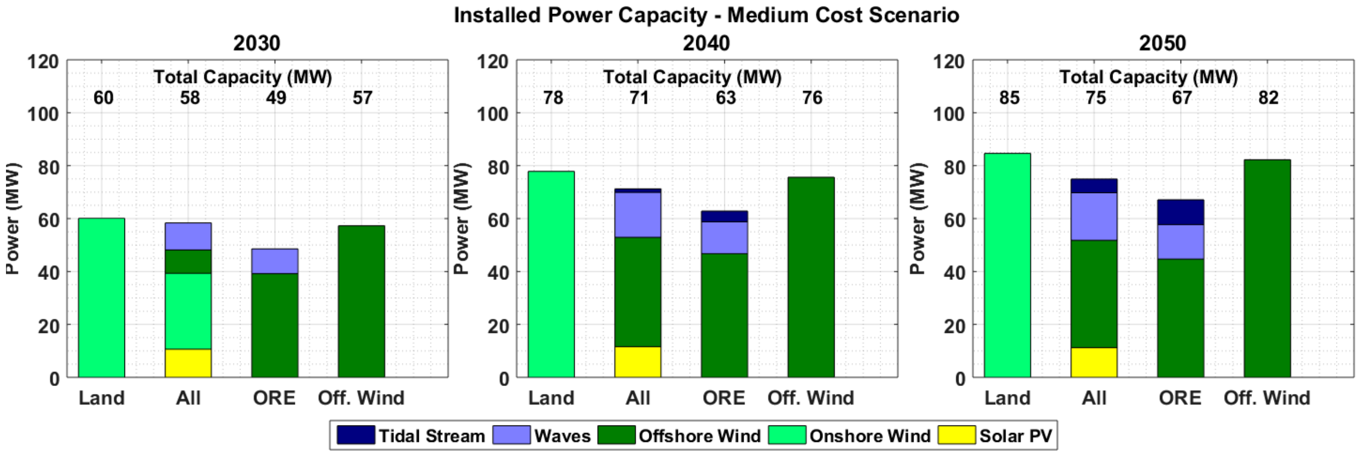

Figure 7. Total installed power capacity for three different time horizons and the closed-grid case, considering the medium-cost scenario.

The benefit of the complementarity between different renewable energy sources is further highlighted in Figure 8a, depicting the energy storage needs, and Figure 8c, showing the excess of electricity production as a percentage of the total consumption. Adding wave and tidal to offshore wind decreases the necessary storage capacity by 30% in 2030 and approximately 35% in 2040 and 40% in 2050. However, the all-energies scenario always presents the lowest need of storage. Comparing with the ORE scenario, the latter requires almost 30% more storage than that of the all scenarios, but in 2040 the difference decreases to 8%, and in 2050 it is almost negligible.

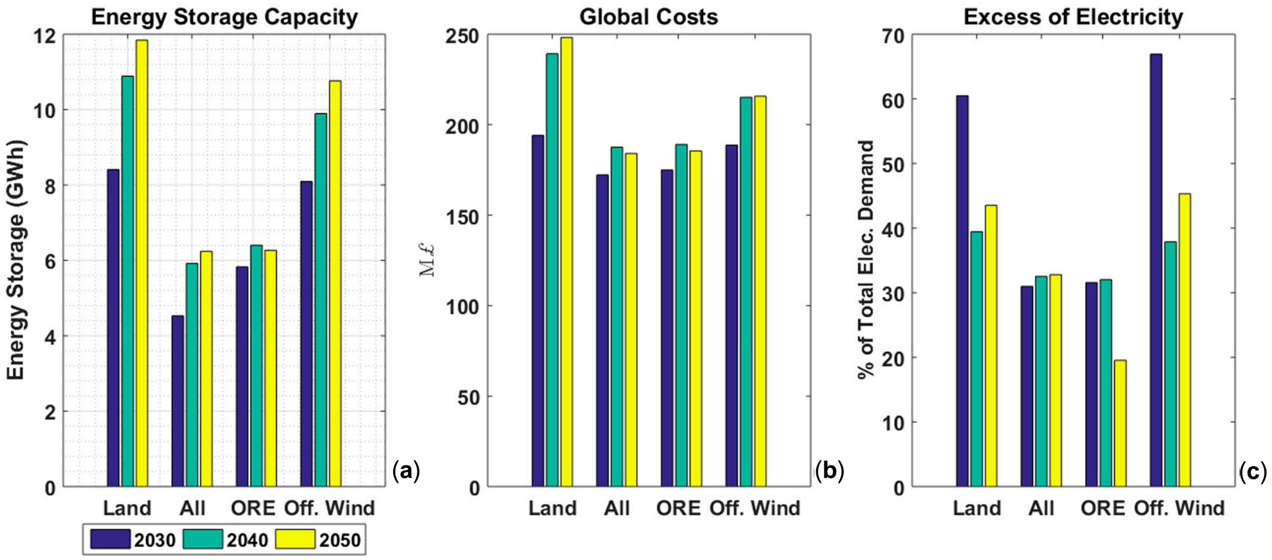

Figure 8. (**a**) Energy storage capacity, (**b**) global costs (CAPEX+ OPEX), and (**c**) excess of electricity generation for three different time horizons and the closed-grid case, considering the medium-cost scenario.

The energy storage is exclusively supported by hydrogen. As presented in Table 2 and discussed in Section 3, the ratio of power to storage capacity for lithium-ion batteries is 1, whereas for hydrogen it is 250, in accordance with the cases presented in the 2018 BEIS report. Hence, the cost of the hydrogen facility per MW is higher than the batteries, but it is considerably lower if it is determined per MWh. The peak demand is relatively low (around 32 MW), so it is significantly more relevant for the solution to have a large storage capacity.

Regarding the excess of generated electricity in Figure 8c, the all-energies and ORE scenarios present similar lower excess generation relative to the other two scenarios, which results from a higher potential of the complementarities between the variety of technologies. When comparing the ORE scenario with having only offshore wind, the latter always has more excess of production, up to twice that of the ORE case.

Lower generation of installed power capacity and lower energy storage needs tend to lower global costs. This is illustrated in Figure 8b. Both the all-energies and ORE scenarios consistently present the most reduced global costs. Interestingly, the ORE scenario is just slightly higher, with differences of 1.5% and less. Having offshore wind alone increases the global costs relative to the ORE scenario by 8%, 14%, and 16%, for 2030, 2040, and 2050, respectively.

Another aspect that is interesting to look at is the variation of the instantaneous power fed into the grid. Given the resolution of the accessible data and also the available computational resources, the model's inputs and results represent cumulative values over one hour. Having in mind the limitations in time resolution, statistical parameters regarding the time series of the total power (summing the contributions of the different sources of each scenario) are shown in Table 5, namely, the mean value, the maximum, the standard deviation, and the root mean square. As there is more complementarity between the sources in the all and the ocean scenarios, it yields lower maximum of the hourly average power and standard deviation values. This may represent gains in grid stability and lower costs to the system in terms of power electronics to properly manage power variations.

Table 5. Statistics of power time series.

	Statistics of the Power Time Series (MW)											
	Mean			**Max**			**STD**			**RMS**		
Commissioning Year	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Land	32.4	41.9	45.6	59.6	77.2	83.9	18.4	23.8	25.9	74.5	96.4	104.9
All	27.0	34.7	36.4	51.4	63.6	65.0	12.8	15.6	15.7	59.8	76.2	79.2
ORE	27.8	35.3	36.8	46.8	60.7	64.8	13.9	16.7	16.4	62.1	78.0	80.6
Offshore Wind	33.6	44.3	48.2	56.6	74.7	81.2	18.4	24.3	26.4	76.6	101.0	109.9

4.2. Grid with Import and Export

The outcomes presented in this subsection pertain to a model version that accommodates the possibility of electricity import. It is assumed that the electricity demand can be met with contributions from other sources not specified in the model, alongside the renewable energy sources mentioned earlier. The electricity supplied by these external sources carries a specified cost per MWh within the model. For each simulation, this cost remains constant throughout the system's entire 25-year lifespan. With reference to BEIS's estimation [17] of approximately 60 GBP/MWh up to 2040, a sensitivity analysis was conducted by testing a range of both lower and higher values. Figure 9 graphically presents the corresponding outcomes for the case of all energies (solar PV, onshore and offshore wind, tidal, and wave). The left graph illustrates the installed capacity of renewable sources, with a dark red line representing the energy storage needs. The central graph portrays the electricity from other sources as a percentage of total consumption, and the right side shows the ratio of the global cost of each solution to the cost if the demand was covered only by import.

For an electricity cost of 10 GBP/MWh, the solution dictates complete fulfilment of consumption by electricity import, that is, zero installed capacity for the five renewable sources. At 20 GBP/MWh, the model yields around 20 MW for offshore wind, corresponding to a penetration in the grid of approximately 55%, as it may be seen in the central line. This integration of electricity from offshore wind leads to a small reduction of the cost compared to the case in which the entire demand was covered by other sources, around 8% (plot on the right). As the cost of the electricity import increases, the amount of offshore wind becomes more predominant and solar PV is included. At 60 GBP/MWh, there are 36 MW of offshore wind installed capacity and nearly 30 MW for solar PV, representing 85% of the demand, with a cost reduction of around 50%. Note that wave is included at 150 GBP/MWh and higher import cost, with installed capacity around 10 MW, and tidal does not present any installed capacity, at least up to 300 GBP/MWh. The energy storage needs to become approximately stable as wave energy is integrated in the system, alongside the solar PV slightly decreasing. At 200 GBP/MWh, electricity from other sources represents only 1% of the total consumption, corresponding to a cost reduction of 80%, and reaching a cost reduction of almost 90% for 300 GBP/MWh as the cost of electricity from the external grid.

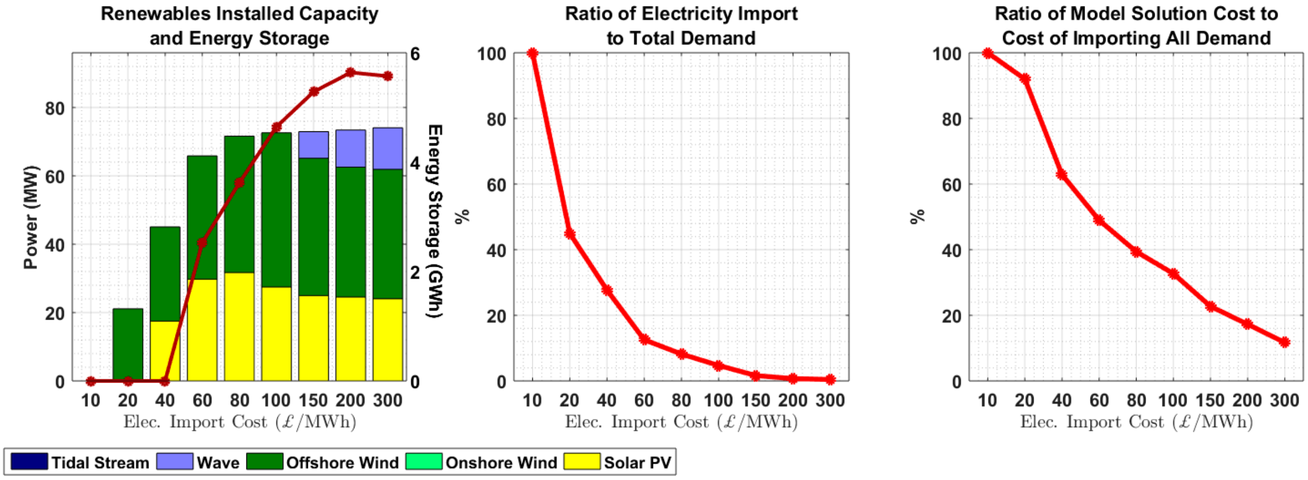

Figure 9. Model solution assuming contribution from other sources for different electricity import costs; all renewables, 2040.

5. Conclusions

In summary, this paper elucidated the methodology employed within the EVOLVE project, presenting its outcomes and implications. The primary objective of this study was to optimize the composition of renewable energy sources to meet the electricity demand of the Orkney Islands. Additionally, the investigation aimed to discern the potential advantages stemming from the incorporation of wave and tidal energies, complementing the existing reliance on offshore wind. Two energy storage technologies were considered in the model: lithium-ion batteries and hydrogen storage. The model favored a large storage capacity and selected the hydrogen storage due to its lower cost.

The model includes simplifications, as outlined in Section 2, and uncertainties common in the projection of future scenarios. Particularly, the demand's time series for one year was replicated throughout the 25 years of the plant's lifespan, and the same was assumed for the generation time series. Moreover, the specific deployment locations and grid interconnections were not considered. Nevertheless, the solutions derived from the model effectively capture the overarching trends within the energy system. These results are succinctly encapsulated in Section 4.1. The most relevant outcomes underscore the advantages arising from the integration of ocean energies, namely, wave and tidal stream, in contrast to a system with other sources, particularly a system exclusively dependent on offshore wind. This integration capitalizes on the synergistic interplay among these sources, manifesting in various dimensions:

- Reduced overall installed generation capacity, around 15% to 20% reduction.
- Diminished requirements for energy storage, from 30% to 40% less.

- The confluence of these factors culminates in a more economically efficient grid, presenting 7% to 14% lower costs relative to the only-offshore-wind case.
- An attenuation of up to 55% of surplus electricity generation, thereby circumventing the associated grid adaptation costs.
- A smoother hourly averaged power delivered to the grid, which may bring benefits in terms of power variation management.
- Anticipated reductions in both generation and storage installed capacities inherently correspond to lower carbon emissions throughout the system's lifecycle, although this aspect has not been quantitatively estimated within the present model iteration.

Also, interesting to find is that the global cost of the scenario including offshore wind, wave, and tidal is just slightly more expensive than the case that additionally considers onshore wind and solar PV, by 1.5% more in 2030 and less than 1% in 2040 and 2050. Another scenario studied considered the import of electricity, besides the local renewable sources, testing a range of electricity cost from the mainland. In summary, as the import cost increases, the integration of renewables expectedly becomes more cost-effective, with offshore wind, solar PV, and wave energy being included in the solution for import costs starting from 20 GBP/MWh, 60 GBP/MWh, and 150 GBP/MWh, respectively.

Despite the model's reliance on certain high-level assumptions, the outcomes unequivocally endorse the value of integrating wave and tidal sources within the renewable energy mix. These findings, coupled with ongoing research, should galvanize diverse stakeholders to make administrative and technical preparations, fortify the sector, and foster the essential supply chain. These collective endeavors align with the overarching aim of cultivating an economically sustainable, low-carbon, and more self-reliant European energy landscape.

Author Contributions: Investigation, M.V. (Miguel Vicente); methodology, M.V. (Miguel Vicente) and A.I.; software, M.V. (Miguel Vicente); writing—original draft, M.V. (Miguel Vicente); writing—review and editing, M.V. (Mário Vieira), F.X.C.d.F. and J.C. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data necessary to this work was publicly available online in [17–22]. Besides the results presented in the paper, there is no other data that resulted from the work.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

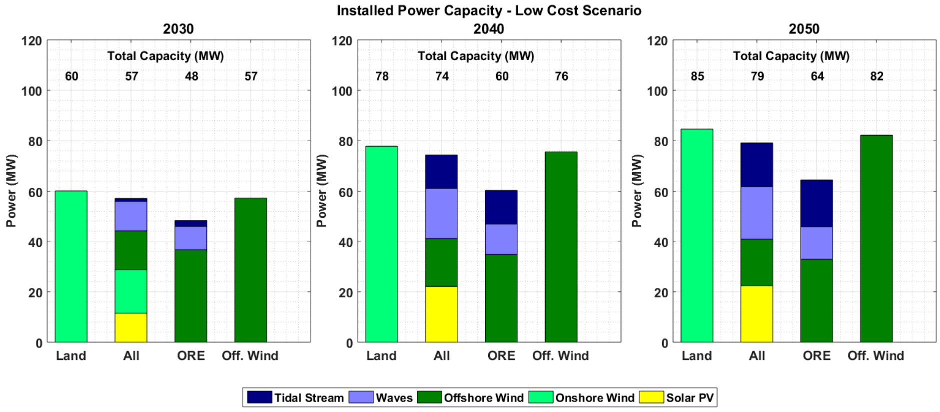

Figure A1. Total installed power capacity for three different time horizons and the closed-grid case, considering the low-cost scenario.

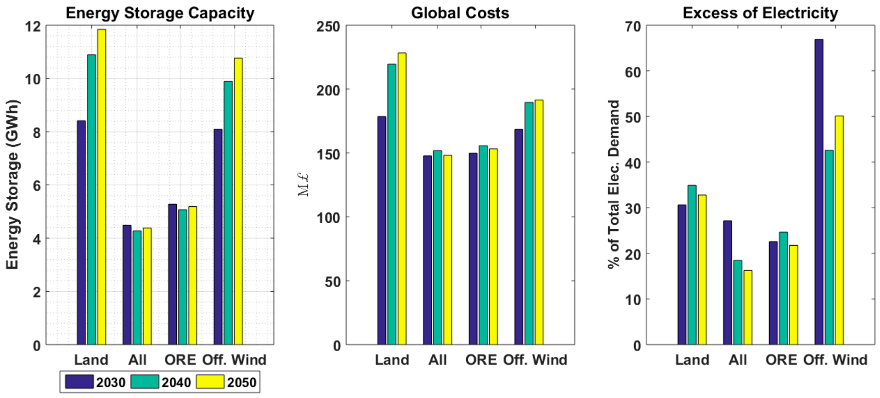

Figure A2. Energy storage capacity, global costs (CAPEX+ OPEX), and excess of electricity generation for three different time horizons and the closed-grid case, considering the low-cost scenario.

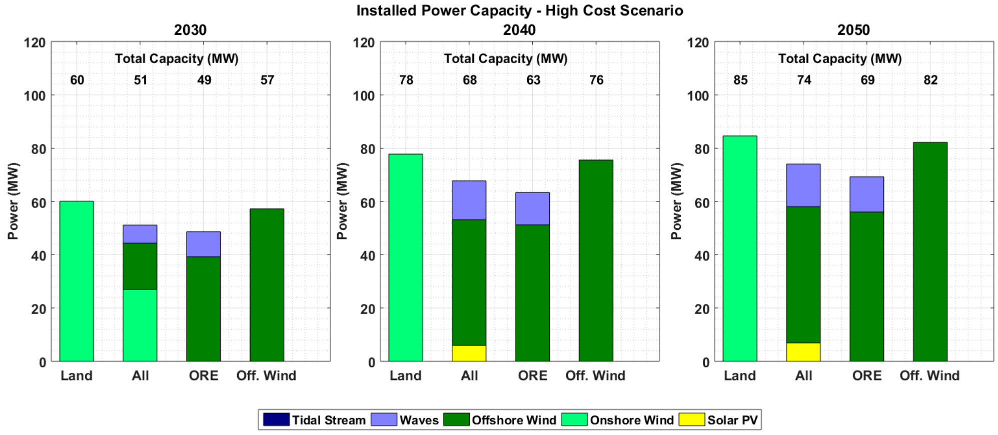

Figure A3. Total installed power capacity for three different time horizons and the closed-grid case, considering the high-cost scenario.

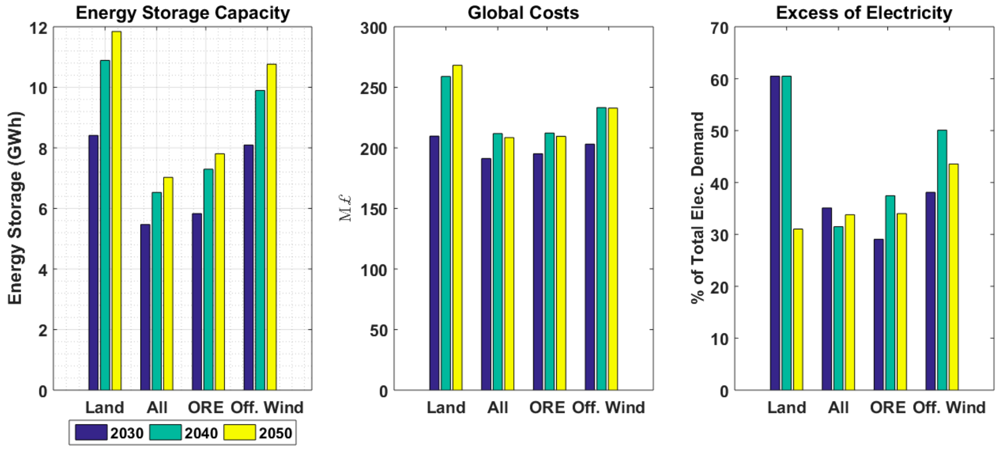

Figure A4. Energy storage capacity, global costs (CAPEX + OPEX), and excess of electricity generation for three different time horizons and the closed-grid case, considering the high-cost scenario.

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