EVOLVE

Place, Time and Value study for Blue Energy across Europe

The system benefits of ocean energy to islanded power systems

EVOLVE technical note: Microgrid modelling study

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SUMMARY - THE SYSTEM BENEFITS OF OCEAN ENERGY TO ISLANDED POWER SYSTEMS

This technical note details the microgrid modelling analysis performed through the OCEANERA-NET EVOLVE project, with the aim of determining the potential role of wave and tidal stream generation within 100% renewable islanded power systems.

The EVOLVE project aims to develop an understanding of the system benefits of ocean energy within future high-renewable power systems, using the analysis of production, supply and demand profiles and credible future energy supply scenarios. It has been postulated that since wave and tidal availability is offset from other renewables such as wind and solar PV, it could be of benefit to system operation to include a more diverse mix of renewables which includes ocean energy.

To test this theory, a microgrid model has been developed representing an islanded system at three different points in time: using projected generation cost and demand scenarios for 2030, 2040, and 2050. The optimisation model developed in this study finds the mix of renewable sources and auxiliary energy storage systems that satisfy the electricity consumption with the minimum global cost (CapEx and OpEx). The greenfield model assumes that there is no installed generation capacity and that the necessary power capacity is installed in a single commissioning year. This is to allow the model to fully optimise the combination of renewable generation and storage to meet demand. The Orkney Islands, Scotland have been used as a case study for this analysis, with demand and generation availability profiles based on historical data from this region.

The main outcome of this study is that the integration of ocean energies (wave and tidal stream) can lead to power system benefits, compared with only making use of more established generation technologies such as solar and wind. Including wave and tidal takes advantage of the complementarity of the renewable resources, which is reflected in several different aspects:

- **Lower total installed capacity of generation required** – scenarios with only offshore wind require 30% to 50% more installed generation capacity relatively to scenarios including wave and tidal energy.
- **Lower energy storage needs** – scenarios including wave and tidal energy required up to two times lower total storage capacity than the offshore wind only scenario.
- **Lower excess of electricity generation**, which otherwise would represent a cost to the grid in order to store or curtail. Scenarios including wave and tidal energy resulted in up to six times lower excess electricity generation than the offshore wind only scenario.
- **Lower total cost** – all of the factors above contribute to a lower cost system (including both CapEX + OpEX) when including wave and tidal energy as part of the generation mix, up to 20% lower than the offshore wind only scenario. This is despite wave and tidal energy having the highest cost of all renewable sources, due to the additional value of their complementary generation profiles.

The results of this study show that including wave and tidal energy in future islanded energy systems can lead to a more efficient grid – both in terms of cost and operation. Lower generation and storage installed capacities will also correspond to lower carbon emissions over the system’s life cycle, though this is not estimated numerically in this study. This work contributes to a portfolio of other studies highlighting the value of wave and/or tidal energy to islanded system operation.

1 INTRODUCTION

The EVOLVE project is funded through the OCEANERA-NET Cofund, with project partners from Scotland, Sweden and Portugal. The key objective of the EVOLVE project is to analyse the overall market value of including ocean energy in the European energy mix; ocean energy here being defined as tidal stream and wave energy.

Three key studies have been undertaken throughout the EVOLVE project, examining:

- The practical deployment potential for wave and tidal stream technologies in the EVOLVE regions of interest;
- The quantifiable system benefits (in terms of economics, carbon reduction and power system operation) of wave and tidal stream deployments in the EVOLVE regions of interest and;
- The potential role of wave and tidal stream within 100% renewable islanded systems, utilising the Orkney Islands, Scotland, as a case study.

This technical note summarises the third of these studies: a microgrid modelling study undertaken with the purpose of gaining an understanding of the optimal mix of renewable energy and storage technologies to meet hourly electricity demand profiles for an islanded system. The study consists of optimising the mix of renewable energy sources that fully satisfy an hourly electricity demand profile, with the minimum cost to the grid (including both capital investment and operational costs). Scenario comparison is used to compare the impact of different combinations of available renewable generation technologies. For example, this study also includes a quantitative assessment of the additional economic value of combining wind, wave, and tidal energy in comparison with only offshore wind.

The Orkney Islands, Scotland have been selected as a case study, with high resource for wind, wave and tidal stream generation. Key modelling inputs include the hourly time-series of the Orkney Islands' electricity demand, the generation availability time-series for different renewable energy sources on Orkney, the costs associated with each form of renewable generation and any constraints that should be considered in the operation of generation and storage. The outputs of the model are the installed capacity of the technology mix selected, the energy storage capacity and the corresponding global costs. The costs included in the model inputs are estimations for plants commissioning in 2030, 2040 and 2050. It should be noted that the scope of this work is not to suggest the ideal generation mix for the Orkney Islands, but use this region as a case study of an islanded system to investigate the potential value of including wave and tidal energy within the wider electricity mix.

The work presented in this technical note has the following aims:

- Adapt WavEC's in-house microgrid model to represent the electrical demand of the Orkney Islands, and generation/storage technology options for three future years: 2030, 2040 and 2050.
- Evaluate the optimal mix of renewable generation and storage to meet demand at least cost for each future year, under a number of generation technology scenarios installing: onshore renewables only, offshore renewables only, offshore wind only, all renewables (onshore and offshore).

2 METHOD

The optimisation model developed in this study finds the mix of renewable sources and auxiliary energy storage systems that satisfy the electricity consumption in an islanded system, with the minimum global cost (CapEx and OpEx). The aim of this modelling is to find the optimal mix of renewable generation and storage for an islanded system, using the Orkney Islands, Scotland, as a case study. As such, this study makes use of a greenfield modelling methodology, assuming that there is no pre-existing installed generation capacity, and that the necessary power capacity is installed in a single commissioning year. The system is assumed to be completely islanded, with no grid import/export capability to other regions. This model is illustrated in Figure 1.

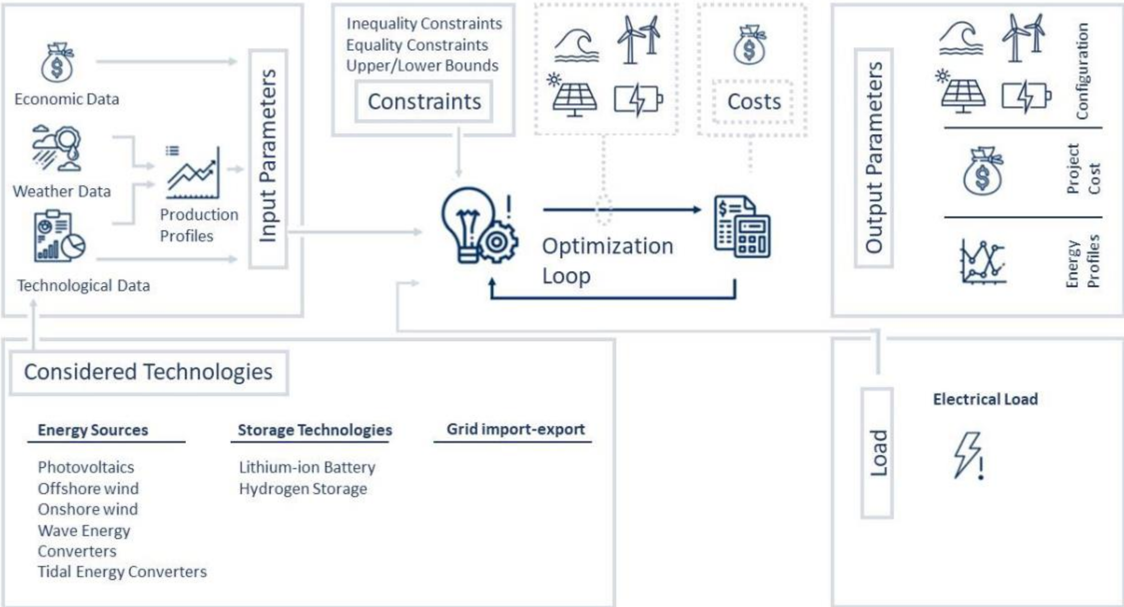

Figure 1. Illustration of WavEC's microgrid optimisation model.

The key inputs of the model are:

- Technology cost (capital investment - CapEx, and operational costs - OpEx) estimations for the years 2030, 2040 and 2050 (from UK Department of Business, Energy and Industrial Strategy forecasts [1], [2]). The wave and tidal stream cost forecasts were provided by EVOLVE project partners. The cost inputs for storage and renewable generation are shown in Table 1 and Table 2, respectively.
- Hourly profile of the electricity consumption over one year for the three future reference years (derived from National Grid historical data from 2019 [3] and scaled up to match the increase in electrical demand in National Grid's future energy scenarios [4]). The resultant normalised monthly average electricity consumption is shown in Figure 2, showing higher demand in the winter months, and lower demand in the summer months.
- Hourly generation availability profiles for each renewable energy technology type per MW of installed capacity (derived from renewables.ninja for wind and solar [5], Copernicus data for wave energy [6] and detailed hydrodynamic modelling for tidal stream [7]). Normalised monthly power production for each renewable resource is illustrated in Figure 2, highlighting the seasonal offsetting between the different technologies, and their complementarity with the electricity consumption profile.
- Storage efficiency, depth of discharge and storage capacity, are taken from [2]. Lithium batteries have an efficiency of 90% and depth of discharge of 80%, they have an energy storage to power rating of 1 MWh/MW. Hydrogen, on the other hand, has an efficiency of 32%, depth of discharge of 100% and energy storage to power rating of 250 MWh/MW.

Table 1. Summary of energy storage system costs

Technology	Commissioning Year	CAPEX £/kW			OPEX £/kW/year		
		Low	Medium	High	Low	Medium	High
LI Batteries	2030	2459	297.3	352.9	2.5	4.4	6.1
	2040	197.2	238.8	284.6	2.0	3.5	4.8
	2050	171.7	208.3	249.0	1.7	3.0	4.2
Hydrogen	2030	1880.8	1968.5	2056.2	19.7	21.9	24.1
	2040	1827.1	1908.8	1990.6	18.3	20.3	22.3
	2050	1795.2	1873.4	1951.6	17.4	19.3	21.3

Table 2. Summary of renewable electricity generation costs

Technology	Commissioning Year	CAPEX k£/MW			OPEX k£/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

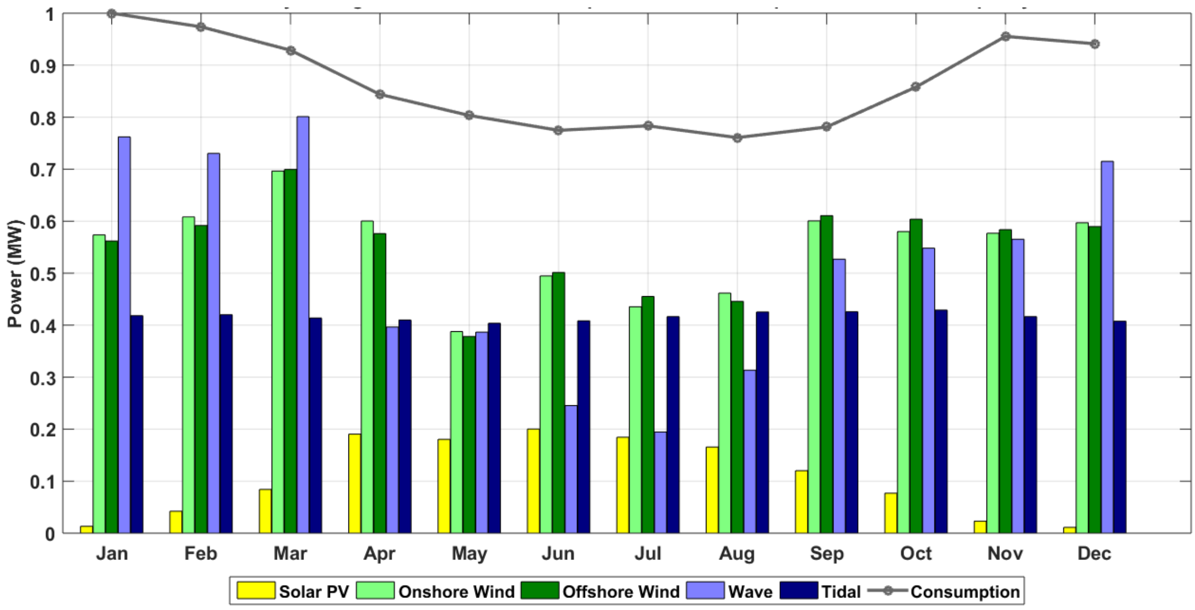

Figure 2. Monthly average normalised consumption and renewable power production per MW of installed capacity.

The model's optimal solution results in the installed power capacity for each renewable source, the energy storage capacity required to manage any discrepancies in electricity production and consumption timings, and the corresponding costs. Since there is no constraint in the electricity production, in other words, it is assumed that there may be curtailment, the excess of generated electricity may be also assessed.

In order to quantify the additional value from including wave and tidal energy within the islanded system, four different scenarios of contributing renewable sources are considered for comparison, namely:

- **Land** - only onshore renewable energy sources (onshore wind and solar),
- **Ocean** - Only offshore renewables (offshore wind, wave and tidal stream),
- **Off. Wind** - only offshore wind,
- **All** - all renewables (onshore wind, offshore wind, solar, wave, tidal stream).

3 RESULTS AND DISCUSSION

The resultant installed capacities for each year and scenario are shown in Figure 3 (renewable energy technologies) and Figure 4 (storage technologies), based on the medium cost assumptions shown in Table 1 and Table 2. The first obvious conclusion across the three years is that when more different types of renewable sources considered, a lower total installed capacity is required to meet demand. This is the result of the complementarity of the different technologies.

The ‘Ocean’ scenario, which can install all of the considered offshore renewable sources, obtains the lowest installed capacity requirement in all years. The installed capacity results for the ‘All’ scenario are comparable with the ‘Ocean’ scenario, with a slightly higher installed capacity of renewable generation and slightly lower installed capacity of storage, shown in Figure 4. The resultant proportional mix of wave, tidal stream and offshore wind in the ‘Ocean’ scenario is sensitive to the input costs, and can be seen to vary between the three years modelled, with more ocean energy installed capacity included in the later years once these technologies have become cheaper. The installed capacity of renewable generation and storage is always highest for the offshore wind only case, with 30% to 50% more offshore wind capacity required for 2040 and 2050 compared with the ‘Ocean’ scenario, and almost double the amount of energy storage capacity required.

Examining the renewable mix for each scenario, it is interesting to note that only onshore wind is installed for the ‘Land’ scenario, while the model also has the option to include solar PV. However, in the ‘All’ scenario, solar PV is installed alongside wave and tidal generation, and forms part of the ideal combination of renewable generation to meet the hourly demand profile. Indeed, for the ‘All’ scenario, a combination of wind, solar, wave and tidal is always installed, highlighting that the combination of multiple different renewable availability profiles provides the optimal solution, rather than only deploying one technology in isolation.

Another interesting comparison can be made between the ‘Land’ scenario and the ‘Off Wind’ scenario, as it can be seen that a slightly lower amount of onshore wind is required to meet demand than offshore wind. Figure 2 shows that both of these technologies have similar capacity factors each month, but interestingly onshore wind hourly availability is slightly higher correlated with the demand profile, and so less is required to meet demand.

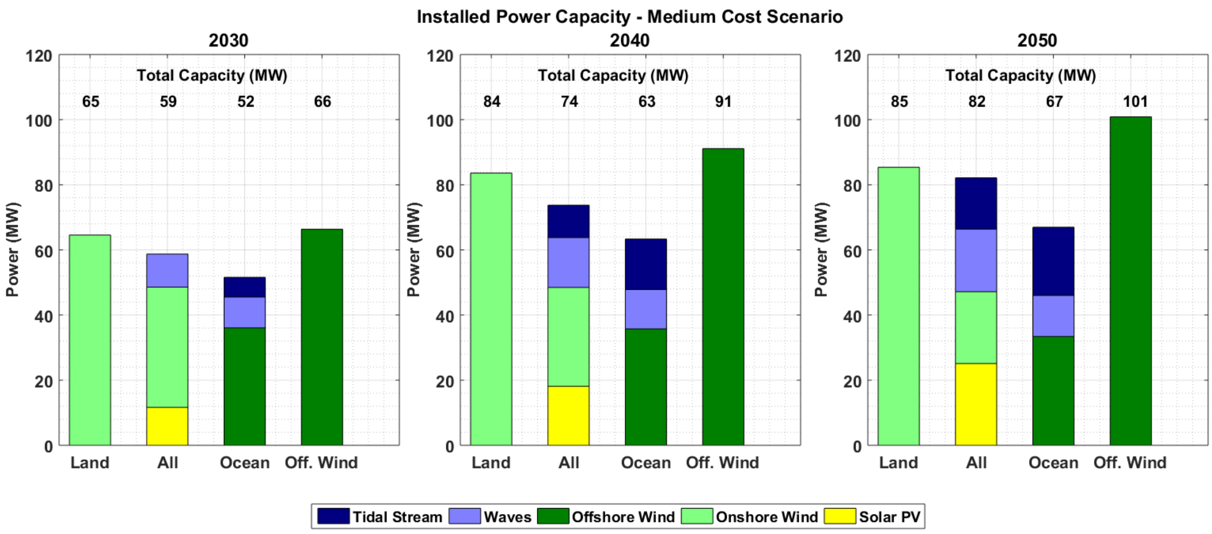

Figure 3. Installed capacity results for different renewable sources scenarios

It can be seen in Figure 4 that the energy storage is almost exclusively supported by hydrogen. The solution attributes a few MWh to Lithium-Ion batteries, but it is so small relatively to the hydrogen results that it is barely visible. This is because while the cost of the hydrogen facility per MW is higher than the batteries, it is able to store a great deal more energy, and so the cost of hydrogen storage is lower if computed per MWh.

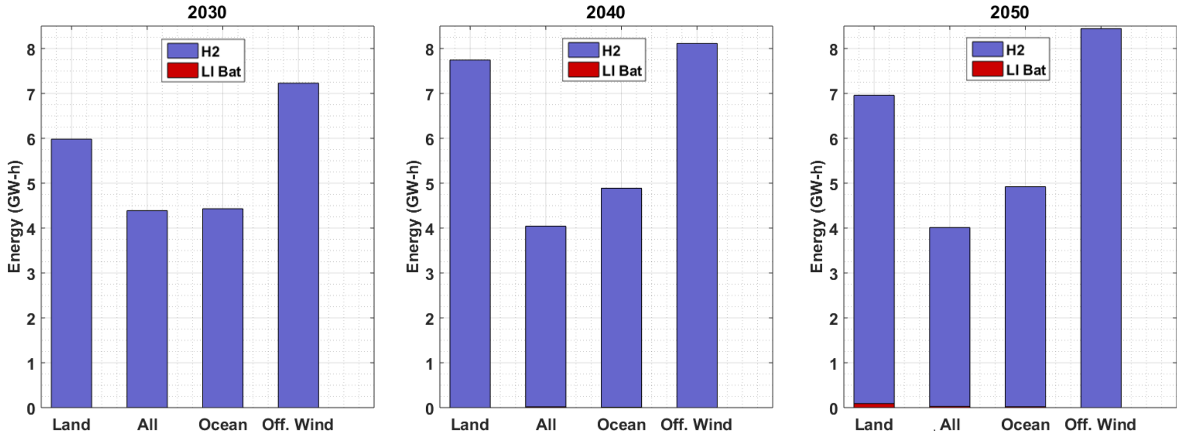

Figure 4. Energy storage required for the solutions of different renewable sources

Figure 5 shows the global cost results for each scenario and year. It can be seen that the lower generation installed power capacity and lower energy storage requirements observed in the 'All' and 'Ocean' scenarios lead to lower global costs. The mix with the three ocean renewables is around 20% less costly than only offshore wind, for 2040 and 2050, and approximately 13% less expensive in 2030.

The 'All' scenario which can install all of the considered renewables sources obtains the lowest costs for the three years. The same reasoning is valid when comparing the solutions of the ocean renewable sources to the only offshore wind scenario. Averaging for the three years, the case with only offshore wind is approximately 23% more costly than the case in which all renewables are considered.

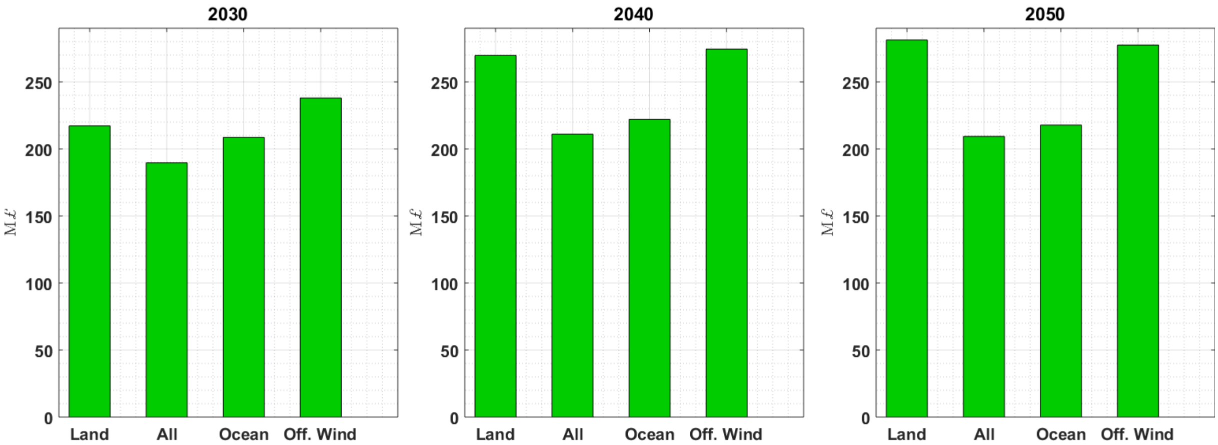

Figure 5. Global costs for the different renewable sources scenarios

Figure 6 shows the excess of generated electricity for each scenario, as a proportion of the total energy demand. The scenario with all renewable sources has the least excess of generated electricity, which results from the higher complementarity between the variety of renewable sources. For the offshore wind only scenario, the excess of electricity generation is 6, 5 and 4 times higher than the ocean scenario, for 2030, 2040 and 2050, respectively. Although it is not quantified by the model, it is expected that higher excess of electricity would lead to higher costs for the system, as excess generation will have to be curtailed or stored to maintain the grid balance.

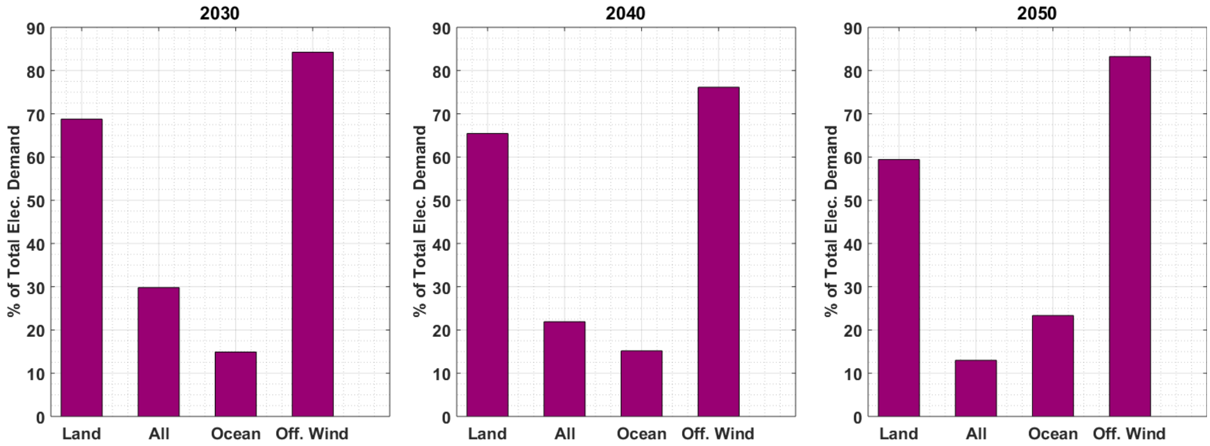

Figure 6. Excess of electricity generation

Finally, Table 3 shows some statistical parameters of the hourly generation time-series for each of the scenarios, namely the mean, maximum and the standard deviation. It can be seen that all of these metrics are lower for the two scenarios which include wave and tidal energy ('All' and 'Ocean'). These results reflect the lower installed renewable capacity, storage and excess electricity generation for each of these scenarios. They also show that the complementarity of the different renewable sources has the potential to decrease peak power and the hour-to-hour variations in power production quantified by the standard deviation. This can result in lower system costs associated with system balancing, curtailments and power electronics to manage power variations.

Table 3. Statistics of the total generation time-series for the renewable sources scenarios

Commissioning Year	Mean (MW)			Max (MW)			STD (MW)		
	2030	2040	2050	2030	2040	2050	2030	2040	2050
Land	35.5	46.0	47.0	64.0	82.8	84.6	19.9	25.7	26.3
All	26.8	30.7	31.3	52.1	59.9	64.5	12.7	12.2	11.7
Ocean	24.7	29.8	33.9	43.6	55.0	65.6	12.7	13.3	14.2
Offshore wind	36.5	50.0	55.4	65.2	89.5	99.1	20.8	28.6	31.7

The main outcome of this analysis is that the integration of ocean energies (wave and tidal stream) brings some benefits relatively to a system only supported by onshore or offshore wind. Including wave and tidal takes advantage of the complementarity of the different renewable energy sources, which is reflected in several aspects:

- lower total generation installed capacity,
- less energy storage needs,
- these two factors lead to a more cost efficient grid,
- lower excess of electricity generation, which otherwise would represent a cost to the grid in order to appropriately accommodate that excess, or it is simply curtailed.

4 LIMITATIONS AND UNCERTAINTIES

As with any energy system modelling study, this work has included various simplifications and assumptions, and it is important to discuss the results in the context of the study limitations.

These include uncertainties involved with generation costs up to 2050. The cost data used in this study has come from government reports and technology developers, but there are a number of uncertainties associated with projecting future generation and storage costs, and these data could be refined further in future. The results will be particularly sensitive to the cost inputs, as the model objective function minimises the total cost of the system.

Another limitation is that only one base year (2019) has been used for demand profile shape and renewable generation availability data. The results will be sensitive to the hourly time series as a key modelling constraint is that demand has to be met with generation for every hour of the modelled year. Further work could include examining if the key trends in results presented here continue when a range of other base years are used as modelling inputs.

It should also be noted that while the greenfield modelling methodology used assumes no previous installed capacity within the islanded system, in reality there is already renewable energy installed capacity in the Orkney Islands. This was to allow for the optimal mix to be selected and examined between scenarios, but it is worth emphasizing that it does not fully represent the current power system. It should be emphasized that the scope of this work is not to suggest the ideal generation mix for the Orkney Islands, but use this region as a case study of an islanded system to investigate the potential value of including wave and tidal energy within the wider electricity mix.

Also, in the results presented here there is no interconnection with mainland Scotland modelled, as the scope of this analysis was to investigate the optimal renewable/storage mix to fully meet demand. In reality there is already a small electrical interconnection between Orkney and Great Britain, with the potential for further grid upgrades in the future. Further sensitivity analysis could be undertaken to investigate the impact of import and export capability with the GB grid.

Finally, it should be highlighted that the results produced in this technical are specific to the case study chosen of Orkney, and will be very sensitive to the regional demand profile and regional renewable availability profiles used. This work already contributes to a portfolio of other studies highlighting the value of wave and/or tidal energy to islanded system operation, such as [8], [9], [10]. Further work could include applying the same methodology and model to a range of islanded systems around Europe, to investigate if the general trend in results is consistent for multiple regions.

5 CONCLUSIONS

This technical note details the adaption of WavEC's in-house microgrid model to investigate the potential role of wave and tidal stream generation within 100% renewable islanded power systems. A model has been created to represent the electrical demand of the Orkney Islands, and generation/storage technology options for three future years: 2030, 2040 and 2050. The optimal mix of renewable generation and storage to meet demand at least cost for each future year has been evaluated, under a number of generation technology scenarios installing: onshore renewables only, offshore renewables only, offshore wind only, all renewables (onshore and offshore).

The main outcome of this study is that the integration of ocean energies (wave and tidal stream) can lead to power system benefits, compared with only making use of more established generation technologies such as solar and wind. Including wave and tidal takes advantage of the complementarity of the sources, which is reflected in various different aspects:

- **Lower total generation installed capacity required** – scenarios only with offshore wind require 30% to 50% more installed generation capacity than scenarios including wave and tidal energy.
- **Lower energy storage needs** – scenarios including wave and tidal energy required up to two times lower total storage capacity than the offshore wind only scenario.
- **Lower excess of electricity generation**, which otherwise would represent a cost to the grid in order to store or curtail. Scenarios including wave and tidal energy resulted in up to six times lower excess electricity generation than the offshore wind only scenario.
- **Lower total cost** – all of the factors above contribute to a lower cost system (including both CapEX + OpEX) when including wave and tidal energy as part of the generation mix, up to 20% lower than the offshore wind only scenario. This is despite wave and tidal energy having the highest cost of all renewable sources, due to the additional value of their complementary generation profiles.

The results of this study show that including wave and tidal energy in future islanded energy systems can lead to a more efficient grid – both in terms of cost and operation. This work contributes to a portfolio of other studies highlighting the value of wave and/or tidal energy to islanded system operation.

Finally, two further technical notes have been published by the EVOLVE project, showing the practical deployment potential for wave and tidal stream for the three EVOLVE regions of interest (Great Britain, Ireland and Portugal), and the potential system benefits of deploying ocean energy at country-scale for the three regions. The latter study has produced results consistent with the microgrid analysis presented here: increasing the proportion of wave and/or tidal stream within high-renewable future power systems results in a higher availability of renewable energy, and thus lower costs.

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