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Optimization of a Tidal–Wind–Solar System to Enhance Supply–Demand Balancing and Security: A Case Study of the Goto Islands, Japan

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Abstract: Due to the expected increase in electric power demand in the coming decades and the economic and environmental issues caused by power generation from the combustion of hydrocarbon fuels, the integration of renewable energy into the grids of remote islands has attracted attention. Among all renewable sources, tidal stream energy shows potential to contribute positively in areas with strong tidal currents due to the predictability and semi-diurnal periodicity of the resource, which makes it compatible with short-term energy storage. However, its performance in areas with lower available power density has not yet been addressed. In this paper, energy systems for the Goto Islands, Japan which combine solar, offshore wind, and tidal energy are evaluated based on whole-system performance indicators such as the annual energy shortage and surplus and the battery load factor. Without energy storage, an energy mix of 31% solar, 47% offshore wind, and 22% tidal energy provides the lowest values for annual energy shortage (29.26% of total power demand) and surplus (29.26%). When batteries are incorporated into the system, tidal stream energy is the main contributor to reducing these two parameters, with values up to 23.58% and 19.60%, respectively, for the solar and tidal scenario with 30 MW of installed storage capacity. These results show the advantages of tidal stream energy exploitation in stand-alone energy systems, even with relatively low capacity factors (0.33).

Keywords: Goto Islands; tidal energy; off-grid system

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1. Introduction

In recent years, growing concerns regarding climate change and the increase in hydrocarbon fuel prices have led international organizations and national governments to promote a transition from a fossil-based energy system to a zero-carbon scenario for the second half of this century. In the case of Japan, this process is expected to boost electricity demand by 30–50% by 2050, and 50–60% of this demand is to be covered by renewable energy sources [1]. Due to the geographic characteristics of the country (an island state with high population density), the Japanese government is promoting the development and exploitation of marine energies. The first round of offshore wind auctions has led to the installation of 1689 MW divided into three farms in Akita Prefecture. Developments in Chiba Prefecture [2] are planned for the following years. Furthermore, a second round to select operators for a further 1.8 GW has already been launched [3].

In addition to offshore wind resources, recent studies suggest that tidal stream energy may play an important role in the future energy mix in Japan [4]. Regarding its contribution to the main grid, the stability and predictability of this resource can facilitate grid management. Results from a recent resource assessment study for West Japan have suggested that due to the differences in the phase of harmonic constituents at well-separated farms, tidal stream energy can continuously provide power to the grid [5]. Moreover, previous works have shown a crucial advantage of tidal stream energy combined with short-term energy storage over offshore wind when applied to remote islands. Due to the periodicity of tides, tidal stream energy lacks the long periods of high or low power production of wind power, which reduces the utilisation of batteries and increases the amount of power needed from backup supply [6].

The integration of tidal stream energy into microgrids for remote islands is expected to be favorable from an economic point of view. The use of tidal stream energy can help to reduce capital expenditures as, due to the periodicity of the resource, lower storage capacity is needed to store the same amount of energy [7]. Moreover, the resource predictability of tidal stream energy facilitates its integration into small energy systems, thereby avoiding expensive grid updates [8]. Furthermore, as backup supply is usually obtained from combustion-based resources, an increase in the storage load factors would mean a reduction in the costs related to the purchase of fossil fuels [6].

Manchester et al. [9] analyzed the integration of tidal stream energy (0.5 MW) into a system with a 0.9 MW wind turbine and a 0.9 MW distribution grid limit in the Digby Neck region in Nova Scotia, Canada. Energy storage was used to accommodate the excess tidal energy production when renewable energy power exceeded 0.9 MW. Results showed that 91% of total tidal generated electricity was directly exported to the distribution circuit, and a storage capacity of 6.8 MWh ensured that all generated electricity was absorbed by the grid. A more economically advantageous option with a 1 MWh storage capacity was presented as well. Although this reduction in storage capacity (85%) requires the curtailment of the tidal turbine (3.97% of total production), a reduction in the payback period is achieved (35 to 9.3 years).

Nasab et al. [10] studied the case of a hybrid wind and tidal system combined with energy storage and a diesel generator for the remote Stewart Island (408 consumers) in New Zealand. Five scenarios differing in installed capacity for wind and tidal stream energy were analyzed, with the best results obtained for a system with 200 kW and 216 kW of installed capacity for wind and tidal energy, respectively. With this scenario, a renewable source penetration rate of 75% was obtained with an operation cost (0.21 USD/kWh), 8.7% lower than when using only diesel power stations.

The suitability of different energy systems with solar PV, wind, and tidal energy to feed Ilha Grande in Maranhao, Brazil was evaluated in [11]. Among the seven analyzed scenarios for this small island with a yearly average power consumption of 4.17 kW, those involving tidal stream energy conversion provided the longest battery lifetimes and the highest penetration ratios of renewable energy sources. Similar results were found for a rural area in Liaoning Province, Northeast China [12], where different systems with solar PV (Photovoltaic), wind, and/or tidal stream energy combined with conventional battery or hydrogen storage were evaluated. For both storage technologies, the system with the lowest LCoE included the utilization of tidal energy. With conventional batteries, an LCoE of 0.21 USD/kWh was estimated for a grid with solar PV, wind, and tidal energy. For systems with hydrogen storage and fuel cells, the option with only solar PV and tidal energy presented the lowest LCoE (0.32 USD/kWh).

Kouloumpis et al. [13] evaluated the impact of tidal stream energy on the sustainability of remote island energy systems. Comparing two scenarios (one with solar PV plus wind, and another with solar PV plus wind and tidal) for Ushant island, lower values for abiotic depletion potential, acidification potential, eutrophication potential, freshwater and marine aquatic ecotoxicity potential, photochemical ozone creation potential, terrestrial ecotoxicity potential, human toxicity potential, and plastics at the end of life were achieved using the system that included tidal stream capacity. In addition, the benefits of marine renewable energy on coastal communities from a socio-technical point of view were demonstrated by Kazimierczuk et al. [14]. These benefits were due to the positive impact of these technologies on the main objectives emerging from interviews with community representatives of different remote areas in the USA, namely, energy security, energy affordability, energy resilience, environmental sustainability, and economic growth.

Including tidal stream energy in remote grids without energy storage has been considered; Richardson et al. [15] analyzed the techno-economic feasibility of using tidal energy resources to displace diesel-generated electricity in remote coastal communities in British Columbia, Canada, finding four of these communities to be suitable for tidal energy development. Coles et al. [16] evaluated the positive impact of tidal energy on energy system security for the Isle of Wight, UK, an island with larger power demand (approximate population of 140,000), simulating different scenarios using the *EnerSyM-RC* model (Energy System Model for Remote Communities). The options that included tidal stream energy generation provided the lowest annual power shortage and surplus. Furthermore, from the economic point of view, when the reserve energy price exceeded GBP 250/MWh it was the case that incorporating tidal stream energy reduced the LCoE of the whole system.

In the present paper, the case of the Goto Islands in Nagasaki Prefecture, Japan, is analyzed using the *EnerSyM-RC* model, and the results are compared to those obtained for the Isle of Wight [16]. The novelty of this study lies in the following points:

- Evaluation of the viability of incorporating tidal stream energy exploitation in a stand-alone system with large power demand and relatively low tidal energy resource.
- Impact of renewable resources variability; due to its lower latitude, the variability of solar PV power production throughout the year in the Goto Islands is expected to be lower than in the Isle of Wight, which might limit the positive impact of the stability and periodicity of tidal energy in systems with energy storage.
- Impact of the difference in demand profile; while in the Isle of Wight there is a peak in winter due to low temperatures, in the Goto Islands power consumption is higher in the summer months as a result of the air conditioning load.

The rest of this paper is divided into the following sections and subsections. Section 1.1 introduces the area of study. In Section 2 the methodology used is presented, including a description of the *EnerSyM-RC* model and the models used to estimate the power generated from renewable sources. Section 3 presents the results and discussion for systems with and without energy storage. Finally, the conclusions of this paper are summarized in Section 4.

1.1. Location

The Goto Islands are an archipelago located approximately 100 km from Nagasaki. The archipelago consists of five main islands, which form four parallel channels (see Figure 1). Based on December 2022 estimation, the Goto archipelago has a population of 51,942 (Goto, 33,124; Shinkamigoto, 16,631; Ojika, 2187). From the extrapolation of data provided by Kyushu Electric Power Co. [17] for 2021 for its whole distribution area (Kyushu Administration area), the estimated annual energy demand is 352 GWh, with minimum and maximum instantaneous power demands of 25.6 MW and 64.5 MW, respectively. As can be observed in Figure 2, electricity consumption is clearly influenced by the meteorological conditions of the area, with one clear demand peak in August due to the high air conditioning load.

Currently, the main power generation sources in the Goto Islands are solar PV (installed capacity of 23 MW), onshore wind (32 MW), offshore wind (2 MW), and two diesel combustion power stations (60 MW and 21, respectively MW) [18]. The Goto Islands' local grid is connected to the main grid by a 66 kV cable [17] for supply/demand balancing.

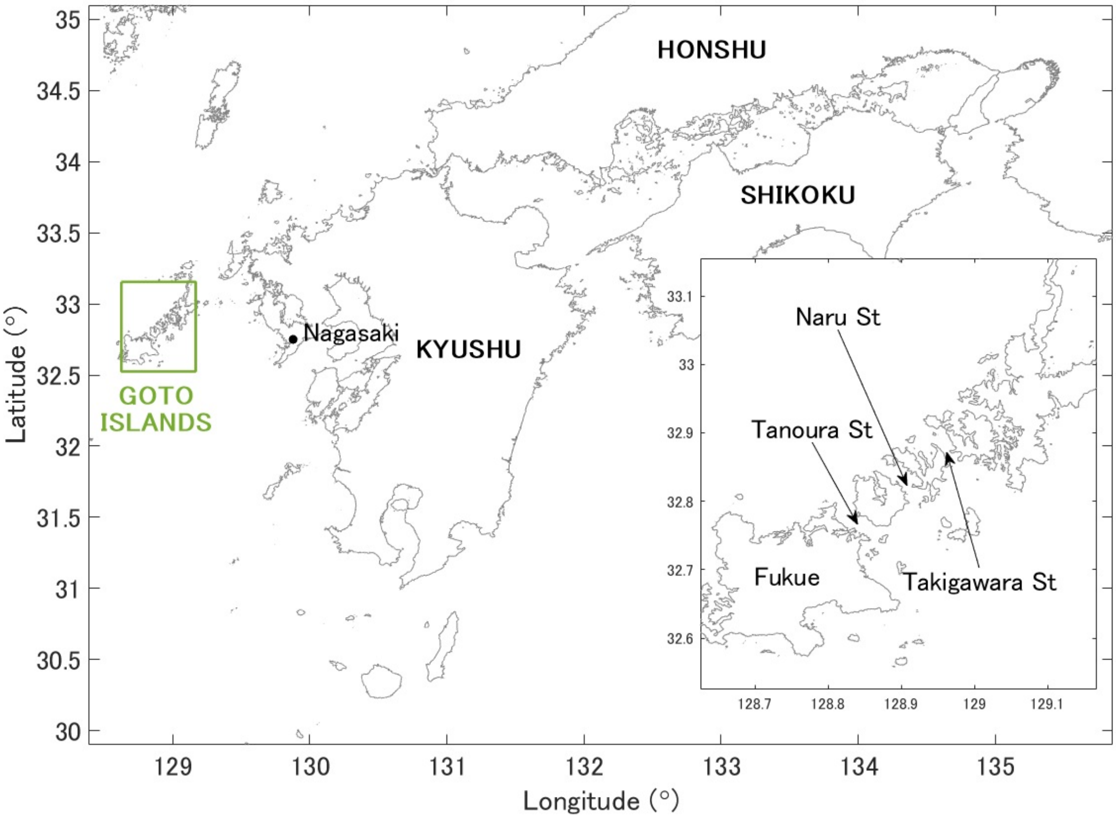

Figure 1. Location of Goto Islands in Japan.

Figure 2. Estimation of annual power demand for the Goto Islands (2021).

According to data measured by the Japan Meteorological Agency (JMA [19]) in Fukue from 1972 to 2022, wind velocities are generally higher during winter, with the exception of two slight peaks in early and late summer corresponding with the Pacific typhoon season (see Figure 3). The graphic representation of averaged monthly solar radiation for the 1972–2022 period measured in the Nagasaki JMA station shows an M-shaped trend (Figure 3), with two peaks in May and August and with a decrease in June and July due to the rainy season. Concerning tidal energy resources, a large amount of water moving from the Pacific Ocean to the Sea of Japan during flood tides and vice versa during ebb tides makes the narrow and shallow channels between the islands suitable sites for the exploitation of tidal stream energy. In this regard, the Japanese Government proposed Naru Strait and Tanoura Strait as test sites for tidal stream energy [20], and a demonstration project in the first of these channels using a 500 kW turbine has provided promising results [21].

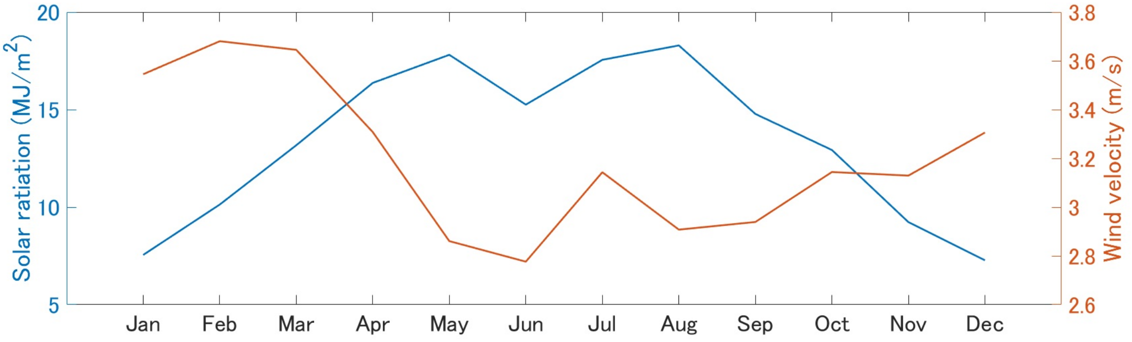

Figure 3. Monthly averaged wind velocity and solar radiation in the Goto Islands based on data measured from 1972 to 2022.

2. Methods

2.1. Energy System Modelling

For easier comparison with other remote island cases, in the present paper the 66 kV connection is ommitted and the Goto Islands are treated as a stand-alone energy system. The model used to simulate the power flow for a local grid on the Goto Islands is the Energy System Model for Remote Communities (*EnerSyM-RC*) [16]. *EnerSyM-RC* is a multi-objective optimization model which aims to improve the supply–demand balancing of local grids. The process followed to achieve the optimum solution consists of simulating various energy mixes differing in solar PV, offshore wind, and tidal stream energy installed capacity during a 1-year period. For the different systems considered for the case study of Goto Islands, solar PV installed capacity ranges between 0 MW and 150 MW at 25 MW intervals, while offshore wind capacity ranges between 0 MW and 125 MW at 25 MW intervals. Tidal stream energy installed capacity was calculated for each case based on the yearly power production from the other two renewable sources and the power demand, ensuring that gross annual renewable energy production matches annual energy demand. Thus, for all analyzed cases the total combined energy production from renewable sources is 352 GWh. The installed capacity for the three renewable energy sources for each of the 31 simulated cases is represented in Figure 4. For cases considering energy storage, battery capacities of 30 MW, 60 MW, 90 MW, and 120 MW were simulated.

The schematics of the power flow in the energy system considered for this study under surplus and shortage conditions are presented in Figure 5 and Figure 6, respectively. Solar PV, offshore wind, and tidal stream energy are used as the primary sources of power generation. If power production is higher than demand, generation is curtailed. In the opposite case, if power generation is not enough to satisfy energy demand, a backup oil generator is used to meet demand. When short-term energy is considered, the battery is charged if power generation exceeds demand until it is fully charged. At that point, power generation is curtailed. Conversely, when generation is lower than demand, the battery is discharged to meet the shortfall. If the battery is empty, backup oil generators are used. The full description of *EnerSyM-RC* can be found in [16].

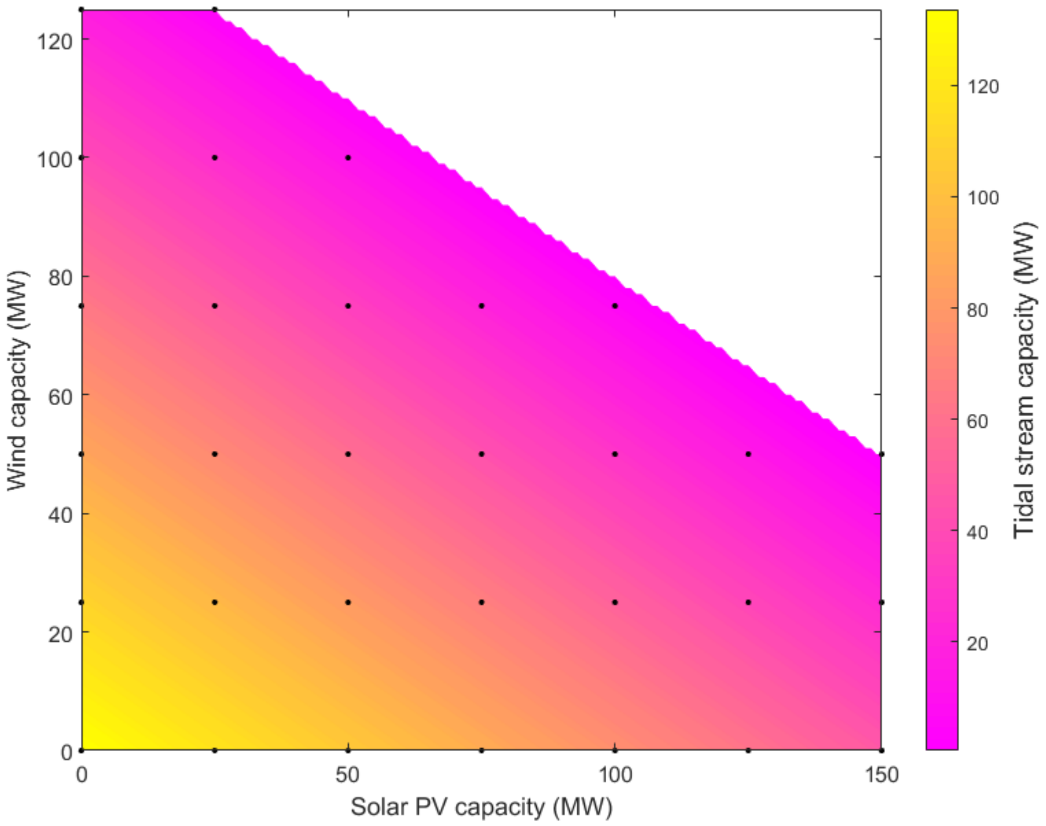

Figure 4. Solar PV, offshore wind, and tidal current installed capacity for each of the 31 analyzed energy systems.

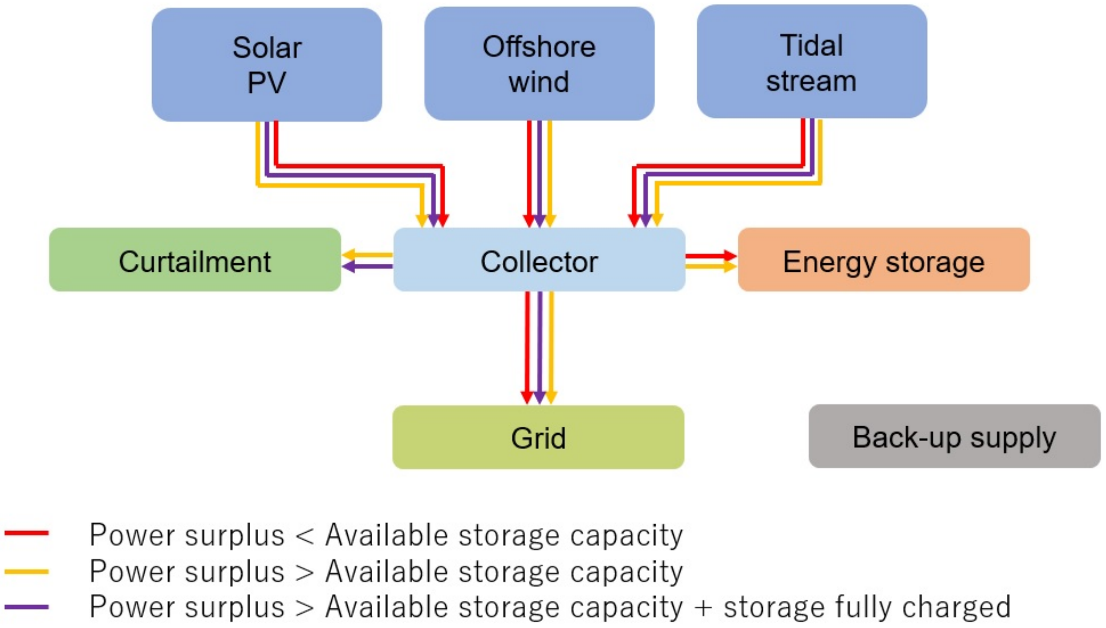

Figure 5. Information and energy flow diagram of the system simulated by the *EnerSyM-RC* model when renewable power production is higher than power demand.

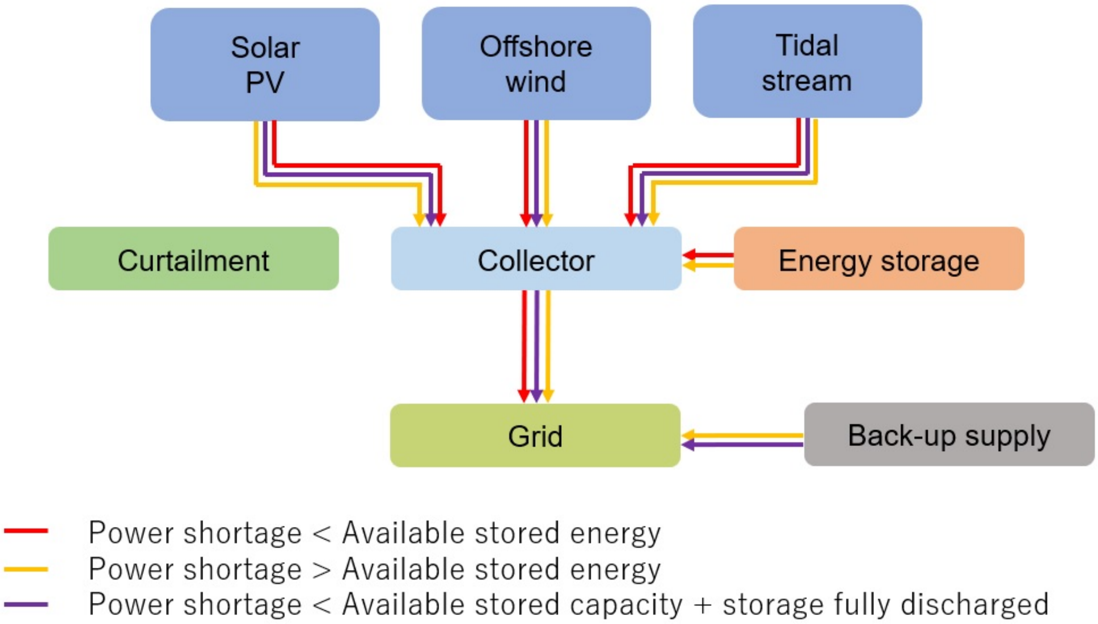

Figure 6. Information and energy flow diagram of the system simulated by the *EnerSyM-RC* model when renewable power production is lower than power demand.

The objective functions of the optimization process are the minimization of annual energy shortage and annual energy surplus. Other perfomance metrics, such as the spatial efficiency and whole-system cost of energy, can be incorporated as well. Annual energy shortage (Equation (1)) is the summation of the hourly difference between power production and power demand when the former is lower. This parameter defines the amount of power required from the reserve supply to meet electricity demand when power generation from renewable sources is insufficient. Annual energy surplus (Equation (2)) is the summation of the hourly difference between power production and power demand when the former is higher. This parameter quantifies the amount of electricity "dumped" by the curtailment of renewable energy conversion:

$$Annual\ Energy\ Shortage = \sum_{t=1}^{l} max(P_d - P_g, 0) \tag{1}$$

$$Annual\ Energy\ Surplus = \sum_{t=1}^{l} max(P_g - P_d, 0) \tag{2}$$

where P_d is the power demand, P_g is the power generated, t is time, and l is the length of the simulated period.

Additionally, the performance of different systems combining renewable energy generation with energy storage were evaluated using the battery load factor. This dimensionless parameter is defined as the ratio of energy discharged from the battery divided by the energy that would be discharged if the storage system were to be continuously discharged at its power rating (Equation (3)).

$$Load\ Factor = \frac{Power\ discharged\ (\mathrm{MWh})}{Battery\ Capacity\ (\mathrm{MW}) \cdot Time\ period\ (\mathrm{h})} \tag{3}$$

Energy System Model Input

The *EnerSyM-RC* was run based on 1-year (2021) hourly data for power demand and power production from solar PV, offshore wind, and tidal stream energy. Data obtained from the Renewables.ninja tool was used to calculate solar PV [22] and offshore wind [23] power production. This tool derives solar PV and wind power from resource data provided by the Modern-Era Retrospective analysis for Research and Applications (MERRA-2) project [24]. The validity of solar PV output estimations from Renewables.ninja has been confirmed by comparison with data from more than 1000 sites and nationally aggregated PV output for six countries, with an RMS (Root Mean Square) error lower than 10.7% in all cases [22]. Regarding hourly wind power output estimations, the tool has been validated by comparison with hourly national capacity factors for eight states, with R^2 values from 0.76 to 0.96 and RMS errors between 3.1% and 7.4% [23]. For the present study, solar PV power output was calculated for 32.8164° latitude and 128.9119° longitude considering an azimuth of 180°, a panel tilt of 35°, and no tracking. Likewise, wind velocity obtained for the same position (32.8164° N, 128.9119° E) was used to estimate the offshore wind power production based on the power curve of a Vestas V164 9500 turbine with a hub height of 100 m and capacity of 9.5 MW.

FVCOM (Finite-Volume Community Ocean Model) [25] was used for the estimation of available tidal stream energy resources. The model solves three-dimensional primitive equations for momentum, continuity, temperature, salinity, and density. FVCOM has been confirmed in numerous previous studies as an accurate tool to simulate hydrodynamic conditions in coastal areas with strong tidal currents [26,27]. The computational domain for the model simulating the tidal currents in the waters of Goto Islands covered an area of 52,311 km^2, with cell size increasing from 6500 m^2 in the area of interest to approximately 10 km^2 in the cells adjacent to the open boundary. A minimum distance of 100 km between the open boundary and the area of interest was set in order to ensure that any numerical instability generated in the open boundary did not affect the final results. Depth at all node points was obtained by interpolation of 1 m × 1 m bathymetry data measured with an echosounder in the central parts of the channels and by data from the digitization of NewPec maps [28] for the remaining domain. At every boundary node, the model was forced using tide elevation time series obtained from the Matsumoto model [29], which assimilates TOPEX/POSEIDON altimeter data and tide gauge data from 219 coastal tidal gauges into a hydrodynamic model. Due to computational limitations, water temperature and salinity were considered to be constant in time and space. Prior to the period of study, a spin-up of ten days was added for the stabilization of the model. The timestep was set at 1 s. The domain was divided into nine uniform sigma layers in the vertical direction. The model was validated by comparison of current velocity results using ADCP (Acoustic Doppler Current Profiler) data measured at 32°49′38.8″ N, 128°54′3.7″ E in Naru Strait. At the vertical layer corresponding with the rotor hub of the turbine considered for this work (15 m from the bottom), the correlation coefficient is 0.849 and the normalized RMS error is 0.316 (see Figure 7). The model accurately predicts current velocities during ebb tides, whereas there is a minor underprediction for flood tides. Although the reason for the discrepancy in the model presented in this paper could not be determined, these slight inaccuracies in tidal current models are usually related to limitations arising from a lack of bathymetry data (depth and seabed sediment) in nearby areas, horizontal and vertical discretization, etc. [30]. A more detailed description of the model and its validation is available in [31].

Considering the Betz ratio and current velocity results from the FVCOM model, the 1-year averaged available power density was calculated. Figure 8 shows the resulting Naru Strait maps for layers 3, 5, and 7 (counting from surface). A maximum power density of 1.227 kW/m^2 at the shallowest represented layer is estimated. For the case of the Isle of Wight, tidal energy resource studies have reported estimations for annual power generation up to 3800 MWh considering the Betz limit and a rotor diameter of 16 m [32]. Using these same conversion conditions and the 1-year averaged power density at the most favorable location in Naru Strait for layer 3 (1.227 kW/m^2), an annual power generation of 2161 MWh was obtained, which is slightly more than half of that estimated for the Isle of Wight. Furthermore, in contrast to the semidiurnal tides of the Isle of Wight, the Goto

Islands present mixed semidiurnal tides, which might limit the amount of power that short-term energy storage technologies can charge and discharge.

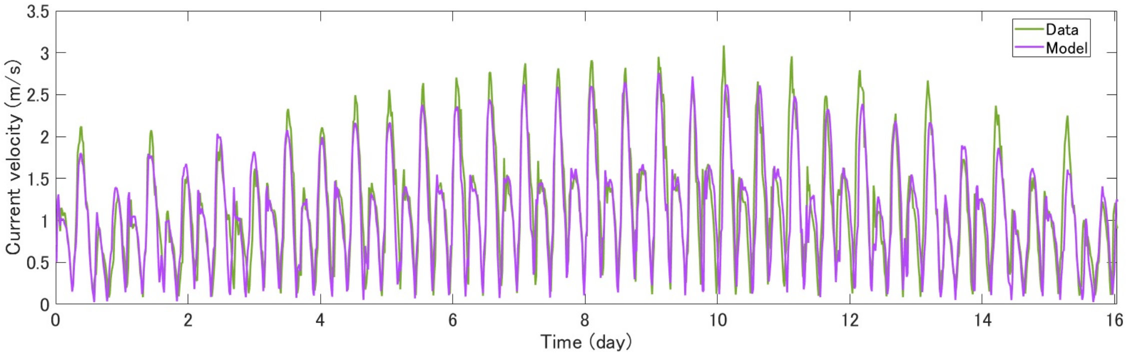

Figure 7. Model validation for current velocity at 15 m from the bottom for a period of fifteen days.

Due to this relatively low tidal energy resource, a generic 0.5 MW turbine with a diameter of 20 m was considered in the present paper to ensure a capacity factor higher than 0.3. Hourly time series of tidal stream power produced by this turbine were calculated based on FVCOM results for flow speed at the cell containing the location 32.8176° N, 129.9092° E, as the resource available at this point is close to the spatial average of the whole tidal site. Regarding vertical distribution, layer 5 was selected to correspond with the rotor hub height. For the simulated period of 1 January 2021 to 31 December 2021, maximum current velocities per tidal cycle at this location and a depth range between 0.31 m/s for the smallest neap tide and 3.06 m/s for the largest spring tide were selected. The time-averaged current velocity for this period was estimated at 1.17 m/s. Hourly power production P per turbine for tidal stream energy was calculated by

$$P = \frac{1}{2} \cdot \rho \cdot V^3 \cdot C_p \cdot A \tag{4}$$

where C_p is the power coefficient of the turbine, ρ is the density of the sea water, A is the area of the rotor, and V is the tidal current velocity. For the generic turbine used for the present work, a C_p of 0.41 was considered.

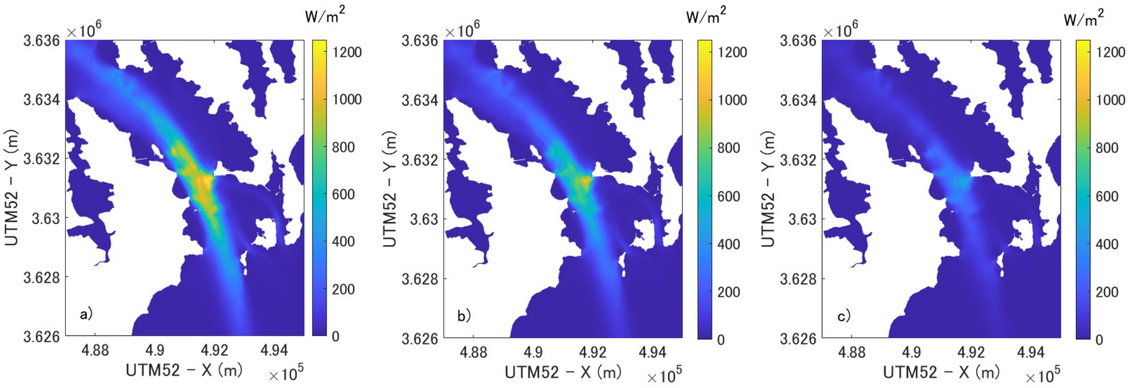

Figure 8. Yearly averaged available (Betz ratio) power density for (**a**) layer 3 (1/4 depth), (**b**) layer 5 (1/2 depth), and (**c**) layer 7 (3/4 depth) in Naru Strait.

For all renewable sources, transmission losses of 10% and power availability of 100% were considered.

For scenarios with energy storage implementation, systems with multiples of 1.5 MW for power rating and 6 MWh for storage capacity were considered, with a round-trip efficiency of 85% and depth of discharge of 100%. These specifications were based on commercial rechargeable lithium ion batteries [33], and are consistent with energy storage conditions used for other similar studies on stand-alone electricity systems on the Isle of Wight [16] and on Grand Canary Island [34].

3. Results and Discussion

The yearly and daily fluctuation in estimated power production (normalized by the installed capacity) and capacity factors for solar PV, wind, and tidal stream energy in the Goto Islands are presented in Figure 9. Monthly averaged capacity factors for solar PV and offshore wind energy agree with the meteorological conditions of the area based on the analysis presented in Section 1.1. In the case of solar PV energy, Figure 9d shows an M-shaped trend, with two peaks in May and October and with values ranging between 0.14 (December) and 0.23 (May). Regarding offshore wind energy, higher capacity factors were calculated for winter, with an additional peak at the end of the summer due to the impact of typhoons. The tidal stream energy resource is the most consistent throughout the year, with monthly averaged capacity factors ranging between 0.31 (March) and 0.37 (July).

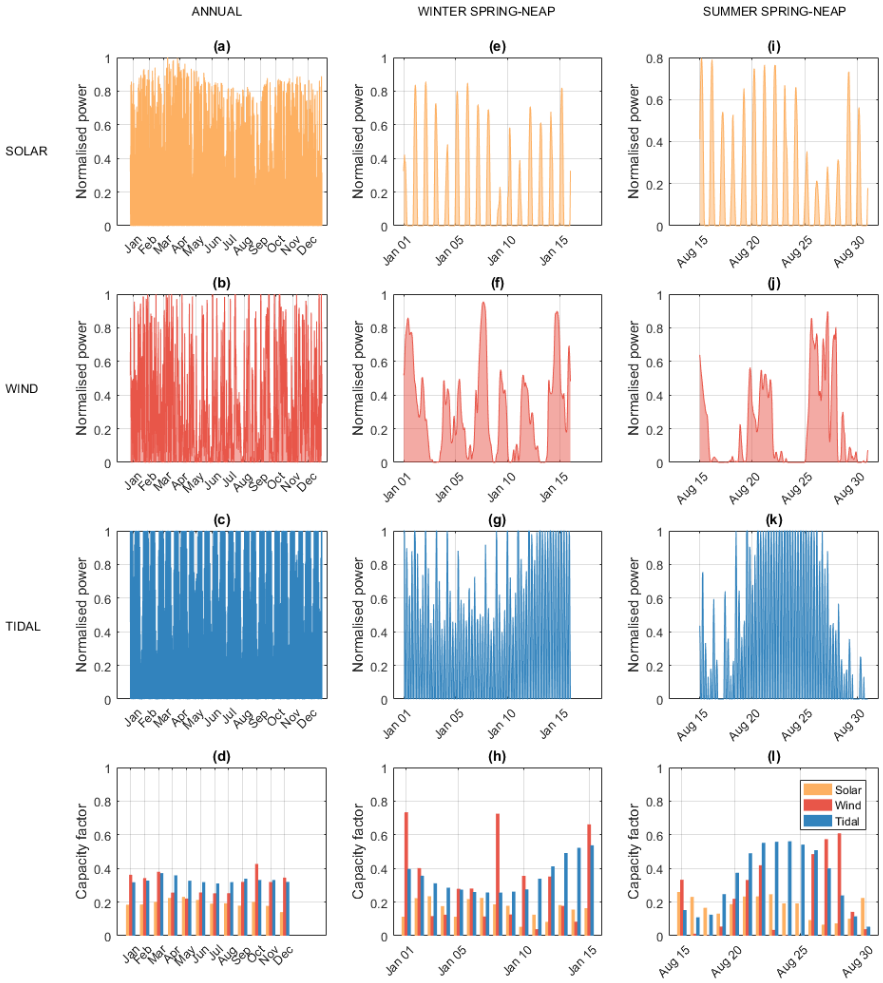

Figure 9. Input solar PV, offshore wind, and tidal stream power data used for energy system modelling. Annual variability of (**a**) solar PV, (**b**) offshore wind, and (**c**) tidal stream power along with (**d**) monthly capacity factors; daily variability in (**e**) solar PV, (**f**) offshore wind, and (**g**) tidal stream power over a winter spring–neap tidal period along with (**h**) daily capacity factors; and daily variability in (**i**) solar PV, (**j**) offshore wind, and (**k**) tidal stream power over a summer spring–neap period along with (**l**) daily capacity factors. For all scenarios, power is normalised to the installed capacity of each technology.

Daily fluctuation in renewable resources was analyzed for two fifteen-day periods in the winter and summer. In both cases, neap–spring tidal cycles are reflected in the daily averaged capacity factor, with higher fluctuations in the second half of August due to the larger tidal range. Solar PV ranks second in terms of resource stability; however, daily capacity factors are clearly lower than those found for tidal stream power, even with neap tides. The inconsistency of wind energy production reported in similar previous studies [6] is observed in the case of the Goto Islands as well. In January, three peaks are estimated on the 1st, 8th, and 15th, while in August two long periods of null generation on the 16th and 22nd are calculated, which represents an obstacle for supply–demand balancing.

Compared to the Isle of Wight case [16], the yearly average capacity factor for tidal stream energy is 17.5% lower. Offshore wind annual averaged capacity factor is lower than in [16] (0.52 for the Isle of Wight and 0.31 for the Goto Islands). Solar PV estimated capacity factor is similar in absolute terms; however, it is more consistent month by month throughout the year for the Goto Islands than for the Isle of Wight. Furthermore, solar PV is the energy resource that better adapts to the power demand pattern in the Goto Islands due to the summer peak related to the air conditioning load.

3.1. Energy System Optimization

Results for the annual energy shortage and surplus for each of the 31 simulated energy systems are presented in Figure 10. The x-axis represents the tidal stream energy installed capacity, while solar PV and offshore wind installed capacity are represented by the colors of the data markers and lines, respectively. These results demonstrate the importance of incorporating these three renewable sources into the system. The convex shape of all curves shows that a too small or too large tidal stream energy share in the energy mix leads to higher annual shortage and surplus. Regarding solar PV, regardless of tidal stream and offshore wind installed capacity, the highest annual energy shortage and surplus are found for scenarios with 0 MW (black dots) and 150 MW (cyan dots). Finally, curves representing scenarios with maximum or minimum offshore wind installed capacity show the worst results for supply–demand balancing in yearly absolute terms.

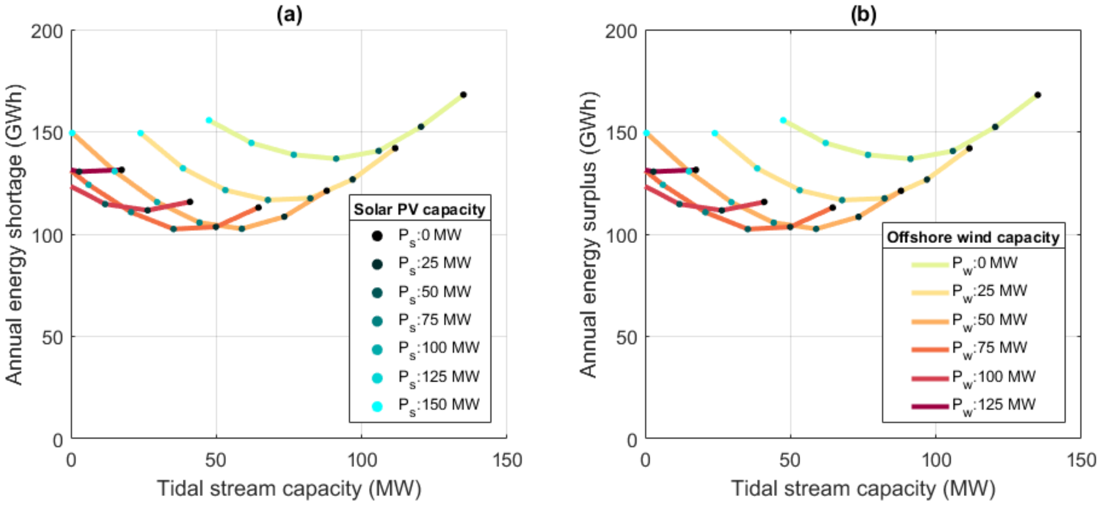

Figure 10. Relationships between tidal stream, offshore wind, and solar PV power capacity and the net annual (**a**) energy shortage and (**b**) energy surplus. Results are based on energy system modelling without energy storage.

The annual energy shortage and surplus are minimized in a scenario using 50 MW (31.25%) of solar PV, 75 MW (46.88%) of offshore wind, and 35 MW (21.87%) of tidal stream capacity, followed closely by a second scenario with respective installed capacities of 50 MW (31.25%), 50 MW (31.25%), and 60 MW (37.5%). In both cases, the annual shortage and surplus are slightly higher than 100 GWh, approximately 0.29 when normalized by the total power demand. Despite the differences in available renewable resources and the fluctuation patterns in power demand, these percentages are comparable to those obtained for the Isle of Wight [16] (35.7% for solar PV, 35.7% for offshore wind, and 28.6% for tidal stream energy). In the case of the Isle of Wight, higher monthly averaged capacity factors for offshore wind energy in winter match with peak power demand due to the lower temperatures. The Goto Islands present a similar pattern in terms of the fluctuation of wind energy throughout the year. However, peak power demand occurs in the summer due to high temperatures and humidity, reducing the effectiveness of scenarios with a large share of offshore wind energy. Furthermore, although this aspect was not considered by *EnerSyM-RC*, as availability of 100% for the three renewable sources was assumed, the higher offshore wind capacity factors at the end of the summer are mainly due to typhoons passing over Southwest Japan. Typhoons and other extreme meteorological events are expected to have a negative impact on the availability of offshore wind turbines, limiting yje contribution of this resource to supply–demand balancing.

Considering the relatively high summer demand of the Goto region, it is surprising that solar PV does not contribute a greater percentage of the total renewable capacity relative to the optimal renewable mix for the Isle of Wight. This result highlights the fact that supply–demand balancing is being driven predominately by winter demand, when solar PV is limited in its contribution. In addition, summer months have fewer daylight hours in the Goto region due to its lower latitude; thus, solar PV can only contribute during the night by using suitable energy storage. This is considered in Section 3.2.

Tidal stream capacity contributes a consistent level of energy throughout the year, with an installed capacity contribution that exceeds 20% in both the Goto region and the Isle of Wight. Tidal stream power features more heavily in the Goto region. One contributing factor to this is the aforementioned fewer summer daylight hours in the Goto region; thus; tidal power can help to compensate for the resulting limitations on solar PV generation.

3.2. Combination with Short-Term Energy Storage

The performance of the 31 possible energy systems combined with short-term energy storage was evaluated based on the resulting annual energy shortage and battery load factor. The aim of the analysis was to understand the contribution of each of the three renewable sources to supply–demand balancing for four representative scenarios: (1) solar PV + offshore wind + tidal stream; (2) solar PV + offshore wind; (3) solar PV + tidal stream; and (4) offshore wind + tidal stream. The installed capacity per renewable technology for each of these four scenarios is shown in Table 1.

Table 1. Installed capacity per renewable resource for the four analyzed cases with integration of short-term energy storage.

	Case 1	Case 2	Case 3	Case 4
Solar PV	50 MW	25 MW	75 MW	
Offshore wind	75 MW	125 MW		75 MW
TIdal stream	35 MW		65 MW	90 MW

Results for annual energy shortage and load factor considering a battery capacity of 30 MW, 60 MW, 90 MW, and 120 MW are shown in Figure 11. As expected, the incorporation of short-term storage improves the supply–demand balancing in the four analyzed cases, and annual energy shortage decreases as installed battery capacity increases. However, the impact of energy storage on the energy system differs depending on the exploited renewable resources. Comparatively low levels of annual energy shortage due to battery installation are estimated for the systems incorporating tidal stream energy generation (1, 3, and 4) due to the stability and periodicity of the resource. Among these three scenarios, the best results in terms of energy shortage reduction are found for the system supplied by solar PV and tidal stream energy due to the respective diurnal and semi-diurnal periodicity of these resources, which enhances the load factor of short-duration energy storage. Regarding storage capacity requirements, the incorporation of tidal stream energy into the system has a positive impact as well. While energy shortage decreases almost constantly with the increase of battery capacity installed for case 2 (solar PV + offshore wind), in the other three scenarios the larger reduction is obtained with the first 30 MW; after which the impact of increasing the energy storage capacity is reduced. An increase of 300% (30 MW to 120 MW) in battery capacity results in a reduction of energy shortage of only 33%, 54%, and 35% for scenarios 1, 3, and 4, respectively. In addition, the results presented in Figure 11 show that even when combined with 120 MW energy storage, system 2 (solar PV + offshore wind) continues to provide a larger annual shortage than the three-resource scenario with no energy storage.

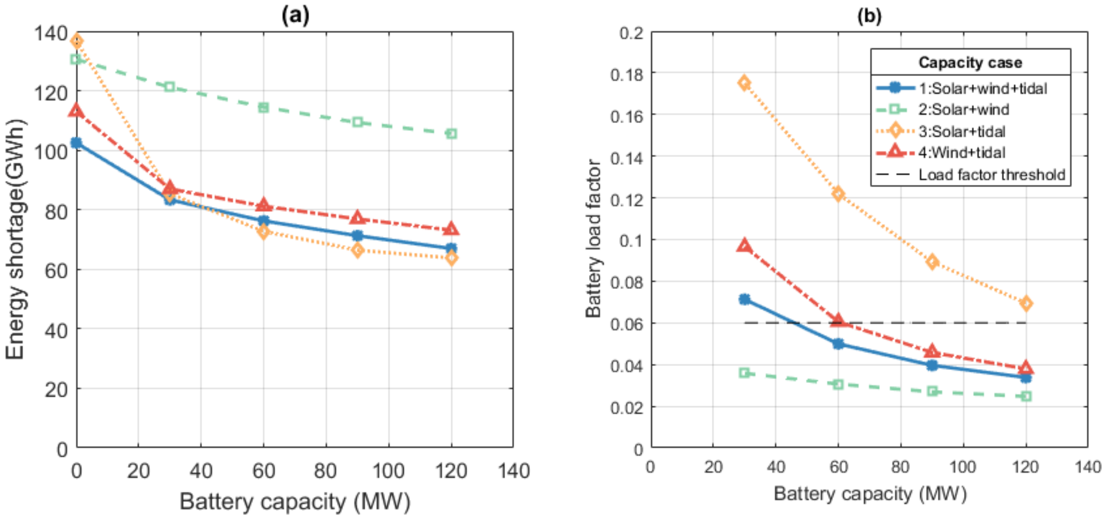

Figure 11. Energy shortage (**a**) and battery load factor (**b**) for scenario 1 (50 MW solar PV, 75 MW offshore wind, 35 MW tidal stream), scenario 2 (25 MW solar PV, 125 MW offshore wind), scenario 3 (75 MW solar PV, 65 MW tidal stream), and scenario 4 (75 MW offshore wind, 90 MW tidal stream). All results are based on energy system modelling without energy storage.

Although these results are consistent with those found for the Isle of Wight, a number of differences can be observed. In [16], the worst performing scenarios were the two-resource scenarios that used solar PV power generation. In contrast, in the Goto Islands, for battery capacity equal to or larger than 60 MW the annual energy shortage with solar PV and tidal stream energy is lower than if the offshore wind is added to the mix. This is related to the high correlation between solar PV energy generation and power demand in the Goto Islands.

Load factors for 30 MW, 60 MW, 90 MW, and 120 MW when combined with the four scenarios presented in Table 1 are shown in Figure 11 (right). In this graphic, a battery load factor threshold of 0.06 is plotted, as this is the minimum value at which short-duration energy storage is considered economically feasible [35]. For annual energy shortage, the worst results were obtained for case 2 (solar PV + offshore wind) due to the low capacity factors from solar PV and the incompatibility of short-duration energy storage with the persistence of strong or weak winds. For this scenario, none of the cases simulated with energy storage (30 MW, 60 MW, 90 MW, 120 MW) provided load factors higher than 0.06. In contrast, the highest load factors were found for the scenario with solar PV and tidal stream energy, which is due to the high-frequency periodicity of both resources. The results suggest that short-duration energy storage would be viable even if 120 MW of battery capacity were installed.

From Figure 11, it must be acknowledged that higher load factors are calculated with offshore wind and tidal stream energy than when solar PV is added to the mix. This can be explained by the low capacity factor of solar PV and its high correlation with the local power demand. Both solar PV power generation and consumption have their peaks in summer and during the day. For this reason, most of the power obtained from this source is used to supply the consumer directly. Furthermore, the incorporation of solar PV energy into the mix means a reduction in the installed capacity (90 MW to 35 MW) of tidal stream energy, the main contributor to elevating the efficiency of short-term energy storage.

These results are similar to those found for the Isle of Wight [16]; the only difference is that scenario 1 shows higher load factors than scenario 4. This is caused by the different power demand variability throughout the year, with lower energy consumption in summer when solar PV generation is higher.

A summary of the main results presented in this section is shown in Table 2.

Table 2. Summary of system characteristics for the Goto Islands and the Isle of Wight.

	Goto Islands	**Isle of Wight**
Min monthly Cf solar	0.14	0.05
Max monthly Cf solar	0.23	0.27
Min monthly Cf wind	0.22	0.39
Max monthly Cf wind	0.43	0.68
Min monthly Cf tidal	0.31	0.40
Max monthly Cf tidal	0.37	0.43
Optimum solution w/o storage	S: 31.25% W: 46.88% T: 21.87%	S: 35.70% W: 35.70% T: 28.60%
Min normalized shortage w/o storage	0.29	0.21
Min normalized surplus w/o storage	0.29	0.20
Min normalized shortage w/o storage *	0.22	0.13
Battery Load Factor *	0.05	0.046

* For the cases with energy storage, the storage capacity installed is 0.08% of power demand in the case of the Isle of Wight and 0.06% in the case of the Goto Islands.

The results presented in this section respond to the three main objectives presented in Section 1:

- Implementing tidal stream energy into stand-alone energy systems with large power demand is advantageous even with relatively low resource availability and mixed semi-diurnal tides, which in principle reduce the load factor of short-term energy storage technologies.
- The lower variability in the monthly capacity factor for solar energy does not lead to a remarkable decrease in the share of tidal energy in the optimum renewable mix.
- This is due to the high correlation between Solar PV production and power demand (peaks in summer and during the day), which reduces the energy storage load factor, demonstrating the strong impact of the power demand on the optimum energy mix.

3.3. Future Work

In this work, the introduction of solar PV, offshore wind, and tidal stream energy in the Goto region of Japan was analyzed. Although the results show that the incorporation of these energy sources into the mix in the appropriate percentages is positive, the proposed scenarios should be analyzed from a socio-economic point of view as well in order to evaluate their viability. In this regard, in addition the LCoE of the energy system, aspects such as the spatial requirement for solar PV and short-term energy storage or co-habitation with the fishery industry and maritime traffic for offshore wind and tidal stream energy should be included in the analysis. Furthermore, new scenarios assuming an increase in power demand due to electrification should be simulated.

Focusing on the aspects considered in the present work, the accuracy of the model can be improved if the spatial variability of the tidal stream and offshore wind energy resources is considered. Furthermore, the relative weight of tidal energy in the optimum scenario may be different if the installation of turbines in Takigawara Strait, which has higher power density than Naru Strait [36], is included. Furthermore, farm spatial distribution and wake losses [37] should be considered for more accurate power production estimation. In addition, the implementation of long-duration energy storage (LDES) should be considered in future works; while LDES technologies may have lower efficiency compared to other options, they can be better adapted for use with the two renewable energy sources with lower LCoE (solar PV and offshore wind). Regarding the *EnerSyM-RC* model, there is a need to build grid constraints into energy system modelling in order to more accurately simulate power flows and the spatial distribution of demand across the region. This new modelling approach will be undertaken using the Python for Power System Analysis (PyPSA) model [38].

4. Conclusions

In this study, the contribution of tidal stream power to the energy balancing and security of stand-alone systems with large power demand and relatively low tidal energy available resources was evaluated. The Goto Islands in Nagasaki Prefecture (Japan) were selected as a case study. The performance of 31 stand-alone energy systems that combine solar PV, offshore wind, and tidal stream energy were evaluated based on the annual energy shortage and surplus system performance indicators. The two best-performing systems used at least a 20% contribution from solar, wind, and tidal capacity (31.25% from solar PV, 46.88% from offshore wind, and 21.87% from tidal stream energy in the first scenario, and 31.25%, 31.25%, and 37.5% in the second).

By contrast, when short-term energy storage was modelled, the best-performing systems in terms of supply–demand balancing and battery load factor used solar PV and tidal energy (i.e., excluding wind). With 30 MW of installed storage capacity, the battery load factor from solar PV and tidal stream power was nearly twice that of the next best case (offshore wind and tidal stream). The main reason for this is the diurnal and semi-diurnal periodicity of solar and tidal resources, which makes them more compatible with short-duration energy storage than offshore wind energy. By contrast, the worst-performing systems excluded tidal stream energy exploitation, which was due to the low capacity factors of solar PV and the persistence of the offshore wind energy resource.

The novel contribution of this work is that it demonstrates that tidal stream energy can provide predictability, stability, and periodicity, which are of great value for stand-alone systems with energy storage even in areas with lower fluctuation of the other cyclic resource (solar PV), relatively low current velocities (max 3.06 m/s), low capacity factors (yearly average = 0.33), and mixed semi-diurnal tides; in particular, this last factor represents an important limitation when coupled with short-term energy storage.

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