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Case Study of a Hybrid Wind and Tidal Turbines System with a Microgrid for Power Supply to a Remote Off-Grid Community in New Zealand

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Abstract: This paper evaluates the feasibility of using a hybrid system consisting of wind and tidal turbines connected to a microgrid for power supply to coastal communities that are isolated from a main supply grid. The case study is Stewart Island, where the cost of electricity, provided by a central diesel power station, is higher than the grid network in New Zealand. Local residents believe that reducing the consumption of diesel and having a renewable source of electricity generation are two of the island's highest priorities. Merging a tidal energy source (predictable) with wind (unpredictable) and diesel (back-up), through a microgrid, may be a way to increase reliability and decrease the cost of generation. Several off-grid configurations are simulated using HOMER and WRPLOT software. Using two wind and four tidal turbines, plus one diesel generator for back-up, is the best design in terms of lower greenhouse gas emissions, higher renewable fraction, and reduced net present cost.

Keywords: microgrid; HOMER Pro; wind; tidal

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1. Introduction

According to the International Energy Agency (IEA) World Energy Outlook report, one in six people in the world lack access to electricity. The distance of main-grid substations and the huge amount of investment needed for governments or companies to provide connections are the main reasons, despite an abundance of renewable energy sources and technologies currently available [1].

This paper models the integration of two available offshore renewable energies, wind and tidal, using a microgrid with the aim to avoid the detrimental effects of diesel on the environment and decrease the cost of electricity in a remote off-grid community. Optimization software is used to simulate electricity consumption from a set of hourly operating loads, then simulate reductions in the percentage of diesel power output dependent on the percentages of wind and tidal power available each hour. The novelty of the paper, with respect to the state of the art, is the use of tidal energy in order to enhance the overall efficiency of the microgrid while preserving its stability. This issue is of particular interest for diesel-based island microgrids that face, constantly, the issues of reducing their dependency from fossil fuels and of enhancing the quality of their supply, by reducing voltage drops and power losses.

From a technical point of view, the contributions of the paper are as follows:

1. Explore the use of tidal energy for off-grid design;
2. Explore microgrid design to link tidal energy with other sources;
3. Explore the use of optimisation software as a method how to apply wind and tidal data into microgrid design;
4. Define a method that could be used to optimise a microgrid of wind and tidal turbines anywhere, in order to facilitate future feasibility studies.

The paper extends previous work of the same authors [2], which evaluated connecting a large wind–tidal hybrid turbine to the main New Zealand grid. In contrast, the current work evaluates the off-grid design for an isolated area, using a microgrid to integrate small separate turbines with battery storage, and retaining a diesel generator for back-up at times when wind and tidal flows are insufficient.

The paper includes four sections. The remainder of Section 1 outlines the concepts. Section 2 introduces the proposed site for the case study, and then the methods. Section 3 presents the results from simulating different scenarios. It contains a discussion on the results of the simulations. Finally, Section 4 reports the conclusions from the case study.

The terms microgrid and mini-grid are often mixed. To understand the difference, first the term "grid" needs to be defined clearly, which is as follows:

A main grid is a network of generation stations to carry power through transmission lines from producers to suppliers, who connect consumers through sub-stations and with distribution lines [3].

A mini-grid has a power rating below 15 MW and is disconnected from larger electric grids [4].

A microgrid is a group of loads and energy resources that are individually controllable and connected, in the range from 100 kW to multi-MW [5]. A microgrid can be operated in grid-connected or disconnected mode [6].

In remote areas, isolated from centralized grids, electricity is already being supplied in a relatively expensive and quick way, through off-grid (or island mode) microgrids. However, reducing the cost of generation and increasing access to renewable energy are two important factors in encouraging greater use of microgrids [7].

The next stage in microgrid design is the integration of renewable energies. Microgrids could contribute to the future of clean energy by the following:

- Better controllability and adaptability [8];
- More diversity and less cost of the new-design generators; they now include solar panels, small-scale wind, efficient natural gas generators, combined heat and power (CHP), and more [8];
- Using various kinds of storage systems, such as batteries, fuel cells and thermal energy storages (TES), at a cheaper price [8,9];
- Possibility of integrating renewable energy sources using artificial intelligence (AI) and machine learning [8].

Laboratory-scale microgrids are used for the experimental investigation of distributed energy resources (micro-turbines, fuel cells, photovoltaics, etc.) [10], hybrid designs [11], and possible components [12]. For real-world installations, commercially available sources of energy, such as diesel generators, hydro generators, photovoltaic arrays, wind turbines, batteries, flywheels and supercapacitors, are being used to construct microgrids for power supply [1].

2. Method

In order to propose a solution for the electricity demand of a remote off-grid community, a number of steps needed to be carried out, which are as follows:

- Selecting a suitable site for the case study;
- Identifying electricity demand, i.e., load profile data;
- Defining all the components of microgrid design including multiple energy resources (turbines and generator), storage device (batteries), rectifier of AC to DC (converter) and predeterminer of electrical system (controller);
- Obtaining environmental data for the energy resources, including fuel type, wind, and water speeds;
- Optimizing the design identifying the location, size, and number of devices required to harness energy resources;
- Feasibility analysis and financial viability of the optimized microgrid design.

2.1. Site Selection

Stewart Island is selected as a case study to evaluate the feasibility of a hybrid system consisting of wind and tidal turbines connected to a microgrid for power supply to remote coastal communities that are isolated from a national supply grid. The island is one of several such communities in New Zealand (Figure 1). The cost of electricity is much higher than on the grid-connected mainland, because power is supplied to just 408 customers from a small diesel power station located centrally in the island's main settlement Oban by the Stewart Island Electrical Supply Authority (SIESA). Its retail charge is 62 c/kWh, of which 23 c/kWh is the direct cost of operating five diesel generators. Replacing diesel by a source of renewable energy is a top priority for residents [13].

Figure 1. Transmission network map [14].

In the case of Stewart Island, fuel cost makes up 40% of operations and maintenance expenditure (Figure 2), so drives the price being charged to customers. Fuel cost is on a 5% annual increase, and additionally, fuel consumption is anticipated to increase 1% annually, which either will increase the cost of electricity for islanders or will decrease the overall income of the supply authority [15].

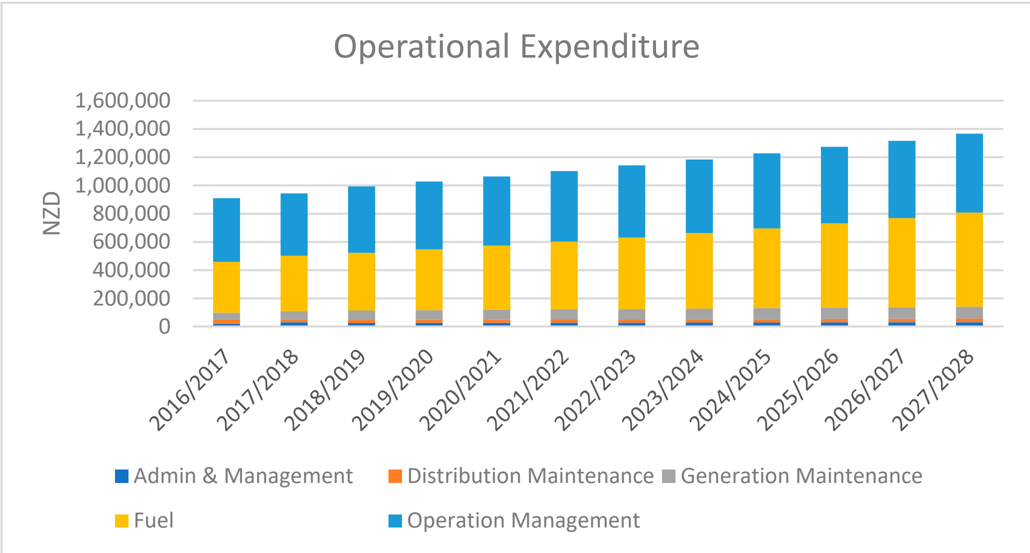


Figure 2. Electricity supply expenditure of Stewart Island [15].

Several investigations have been conducted recently to find a solution for providing electricity at lower cost, such as an undersea cable from Bluff to Stewart Island, providing hydropower from Maori Creek [16], and integrating wind with solar energy [13]. Tidal energy has not been investigated prior to the case study described in this paper.

2.2. Identifying Demand

Stewart Island Electrical Supply Authority data have been used in the case study to estimate monthly and hourly generation. They indicate that the peak values are in January (209 kW) and at 6–7 pm (239 kW), and the lowest values are in August (162 kW) and at 3–4 pm (121 kW) [13].

2.3. Obtaining Environmental Data

Tidal current data have been obtained from a simulation model that MetOcean Solutions Limited (MSL) conducted on an NZ-wide grid with a 0.06° resolution (5.6 × 6.6 km). The simulation nested high-resolution domains over Foveaux Strait (0.004°; 340 × 450 m) shown in Figure 3. The Princeton ocean model (POM) was used to hindcast the tidal current in a vertically integrated two-dimensional mode with boundaries provided from the global TPX07.1 solution [17].

One of these points, referred to as the Foveaux site (Figure 3), has been selected for the case study, because despite being on the opposite side of Foveaux Strait, it appears to have stronger currents (better generation potential) than points close to Stewart Island's coast, and also because the global wind atlas model [18] indicates that this point is in an area with frequent strong winds (high potential for wind energy), shown in Figure 4. For New Zealand, global wind atlas extrapolates data from a network of meteorologic recorder stations operated by New Zealand Meteorological Service (NZMS) and National Institute of Water and Atmosphere (NIWA).

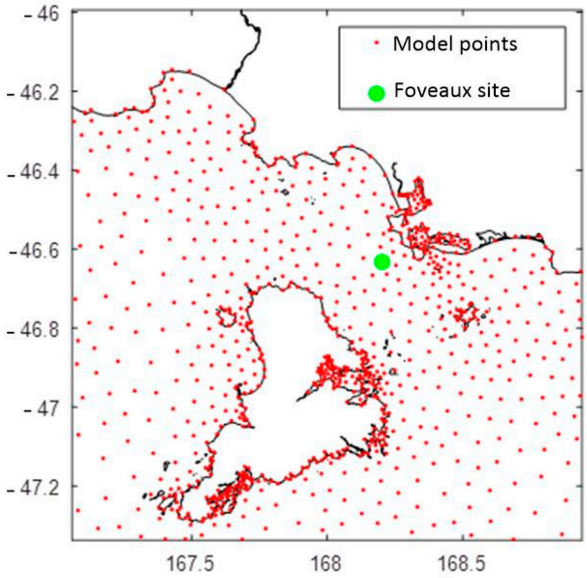


Figure 3. Tidal current model points near Stewart Island from NIWA.

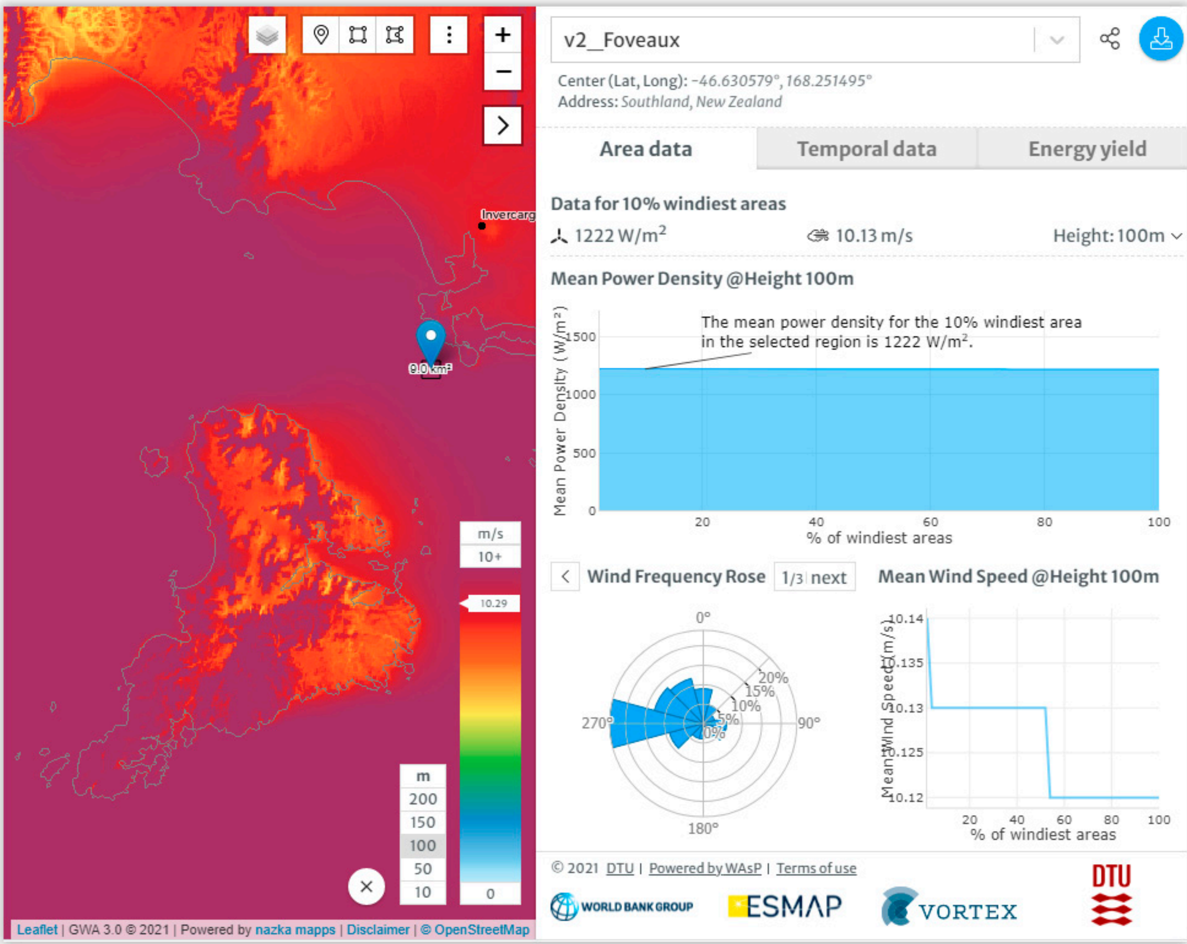


Figure 4. Wind conditions near Stewart Island (**left**) and at the Foveaux site (**right**) [18].

The environmental parameters of the site are summarized in Table 1, and Figures 5 and 6.

Table 1. The environmental parameters of the Foveaux site.

Location	Latitude (deg)	Longitude (deg)	Annual Average Water Speed (m/s)	Water Depth (m)	Annual Average Wind Speed (m/s)
Foveaux	−46.6325° S	168.2025° E	0.52	30	8.31

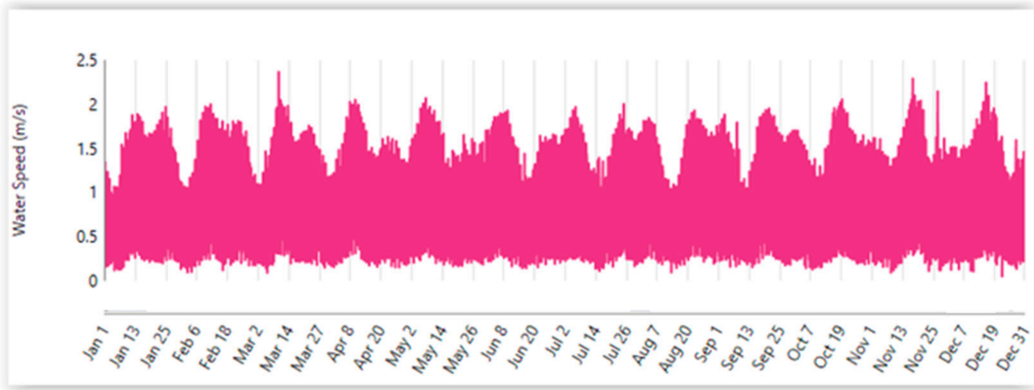


Figure 5. Annual water speed for Foveaux site.

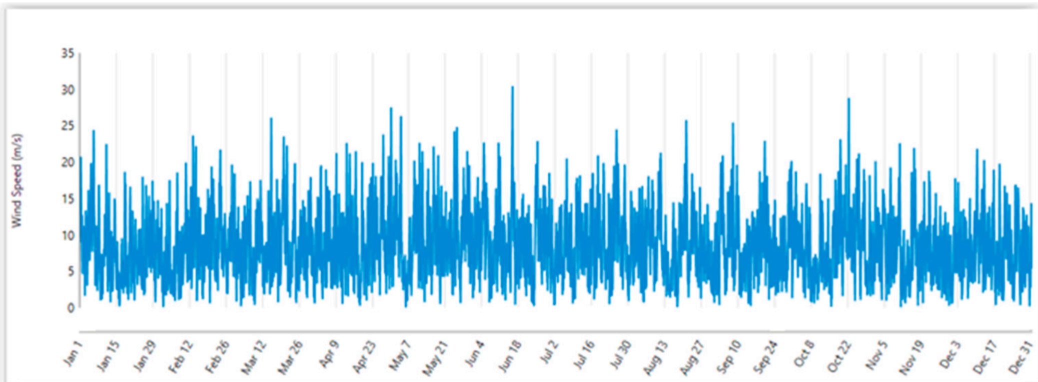


Figure 6. Annual wind speed for Foveaux site.

The last resource input is fuel type for a back-up diesel generator. Biodiesel was selected rather than diesel, because of the following reasons:

- Diesel with 88% carbon content produces more carbon emissions than biodiesel with 77%;
- The lower heating value (LHV) of biodiesel is 43.20 MJ/kg, while this value for diesel is 38.5 MJ/kg [19];
- The price of biodiesel ($/L 0.53) is cheaper than diesel ($/L 1.00) [1].

2.4. Microgrid Components

The microgrid system under consideration consists of wind and tidal turbines combined with a diesel generator and battery energy storage systems (BESS) as shown in Figure 7. A DC bus connects all the components.

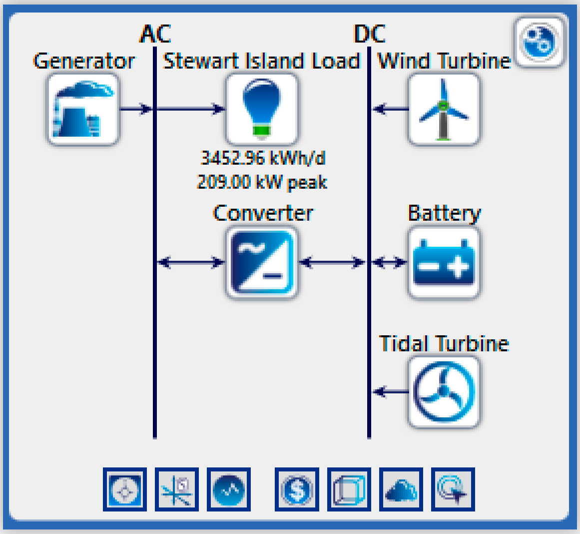


Figure 7. Schematic layout of DC microgrid.

2.4.1. Wind Turbine

A suitable wind turbine in terms of low cut-in speed, a generating capacity capable of meeting peak load, supplying a substantial percentage of peak load and low purchase, installation and maintenance costs is the XANT M-21 (XANT, Brussels, Belgium) (100 kW). The capital, replacement, maintenance, and life of the turbine are taken as $50,000, $50,000, $2500/year, and 20 years, respectively. The power curve and percentage of generation in intervals of 4 m/s shown in Figure 8 are given by Equation (1).

$$P_{wind} = \begin{cases} -0.0018V^6 - 0.07V^5 + 1.0826V^4 - 8.4544V^3 + 36.229V^2 - 78.056V + 66.38 \; for \; V \leq \; 10 \text{ m/s} \\ 100 \; for \; 11 \leq V \leq 20 \end{cases} \tag{1}$$

Other pertinent details for the XANT wind turbine are given in Table 2.

Table 2. Wind turbine details. Adapted from [20].

Wind Turbine	Value
Name	XANT M-21 (100 kW)
Rated Capacity (kW)	100
Manufacturer	XANT
Cut-in wind speed	3 m/s
Cut-out wind speed	20 m/s
Rated wind speed	11 m/s
Hub height	31.8 m
Swept area	346.36 m^2
Rotor diameter	21 m

WRPLOT view software [21] was used to plot wind frequency distribution downloaded from NASA Surface Meteorology and Solar Energy database [22] at the Foveaux site. As can be seen in Figure 9, for 90.5% of the year, the wind speed is more than cut-in speed, so the XANT M-21 wind turbine will be suitable for electricity generation at the Foveaux site.

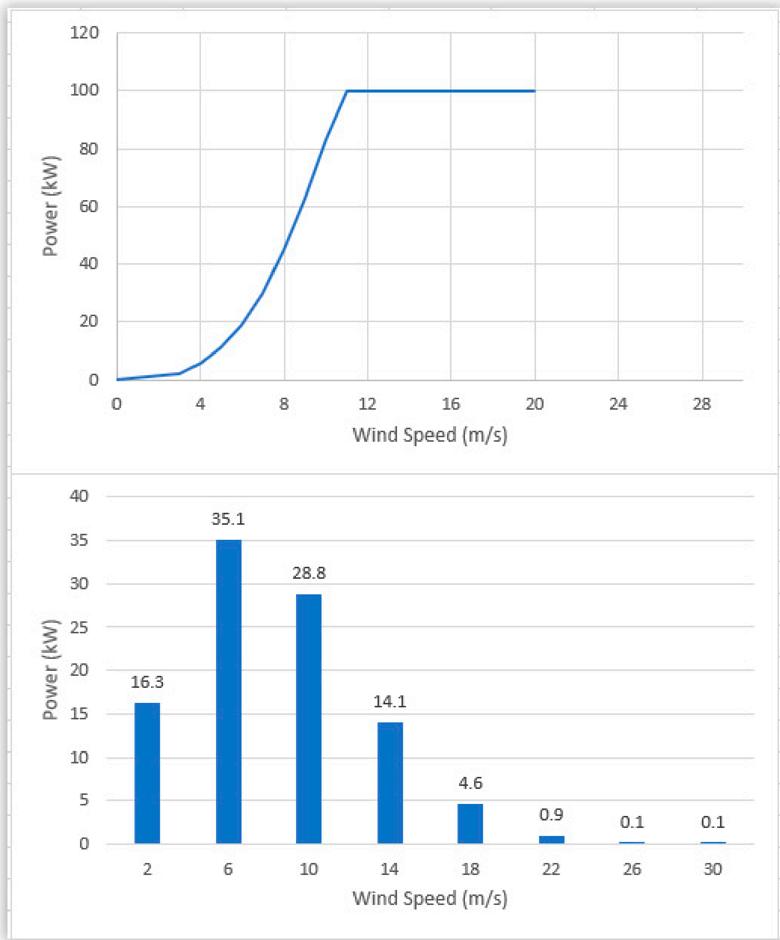


Figure 8. The power curve (**top**) and power generation distribution (**bottom**) of the XANT M-21 turbine.

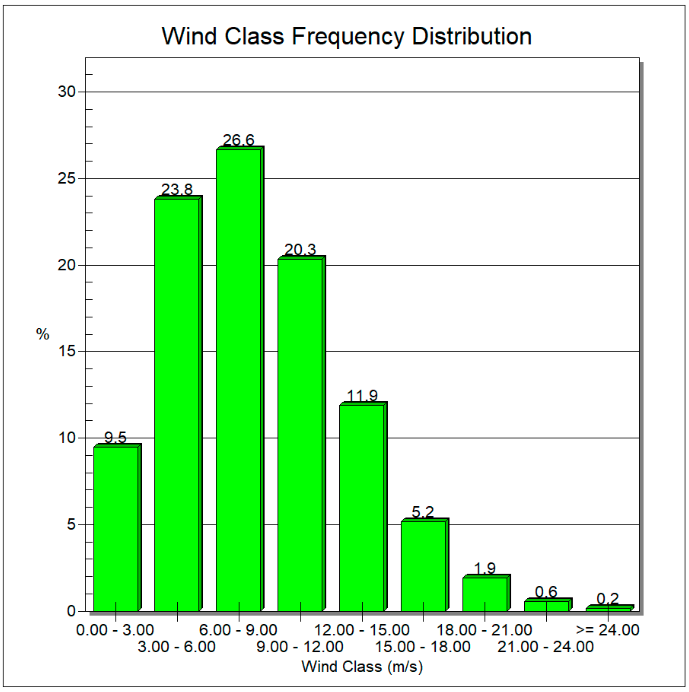


Figure 9. Wind speed frequency distribution at Foveaux site.

2.4.2. Tidal Turbine

A suitable tidal turbine in terms of low cut-in speed, a generating capacity capable of meeting peak load, supplying a substantial percentage of peak load and low purchase, installation and maintenance costs is the Schottel (Schottel, Spray, Germany) (54 kW) bidirectional turbine. The capital (or installation and wiring and mounting expenses), replacement, maintenance, and life of the turbine are taken as $54,000, $54,000, $2700/year and 10 years, respectively. The power curve and percentage of generation in 0.5 m/s intervals shown in Figure 10 is given by Equation (2).

$$P_{tidal} = \begin{cases} 2.0978V^3 + 2.7163V^2 - 1.7909V - 0.2358 \;\; for \; V \ll 2.5 \\ 54 \;\; for \;\; 2.75 \ll V \ll 4.59 \end{cases} \quad (2)$$

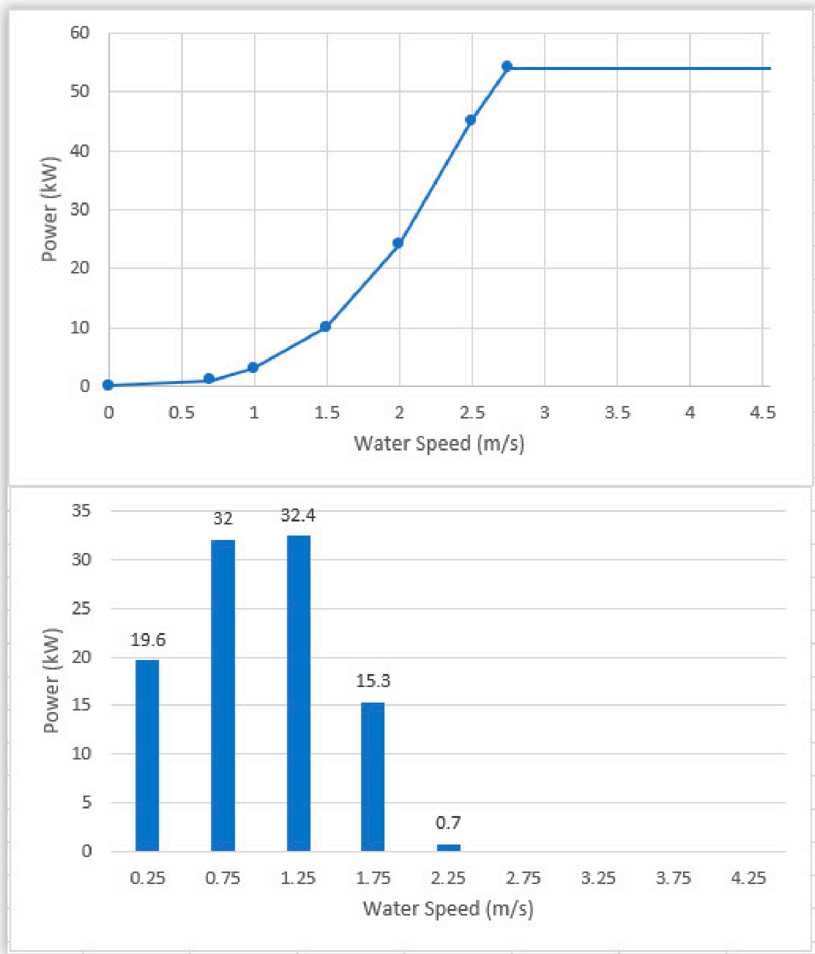


Figure 10. The power curve of the Schottel (54 kW) tidal turbine.

Other pertinent details for the Schottel tidal turbine are given in Table 3.

WRPLOT view software (manufacturer Lakes Environmental, city Ontario, country Canada) [21] was used to plot maximum tidal flow at 5 m above sea bottom. This was obtained by using Python (Python Software Foundation (PSF), Wilmington, NC, USA) code to create a tidal velocity profile from the MetOcean (MetOcean Solutions, Raglan, New Zealand) model's integrated average tidal velocity. As can be seen in Figure 11, water speed for 68.4% of the year is more than cut-in speed, so the Schottel 54 kW tidal turbine is suitable for generating electricity at the Foveaux site.

Table 3. Tidal turbine details.

Parameter	Value
Name	Schottel (54 kW)
Rated Capacity (kW)	54
Manufacturer	Schottel
Cut-in tidal speed	0.7 m/s
Cut-out tidal speed	4.6 m/s
Rated power at	2.6 m/s
Swept area	7.06 m^2
Rotor diameter	3 m

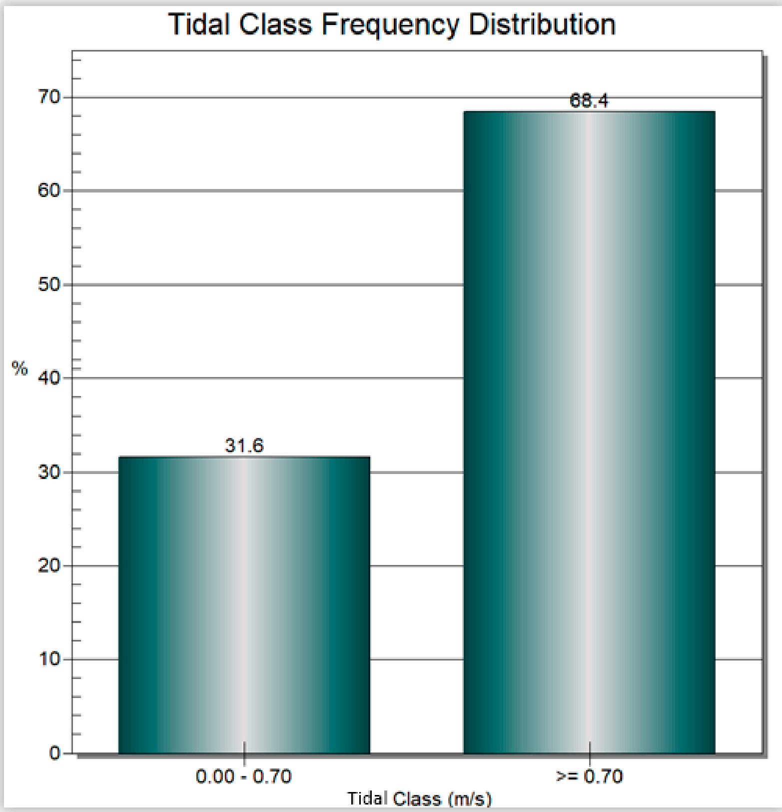


Figure 11. Tidal speed frequency distribution at Foveaux site.

2.4.3. Biodiesel Generator

A 320 kW CAT-400 kVA-50 Hz-PP (Caterpillar, Pontefract, United Kingdom) generator is proposed to cover the base load as a low-level load at less than 25% of nominal capacity. This solution enhances the performance of generation consuming just 6.37 L/h fuel. The lifetime is taken as 90,000 h. Capital, replacement, and O&M costs are $160,000, $128,000, and $4.80/h, respectively [23] as follows:

Capital cost = 500 × 320 = $160,000;
Replacement cost = 400 × 320 = $128,000;
O & M cost = 0.015 × 320 = $ 4.80/h.

2.4.4. Battery Energy Storage

Energy storage is one of the most important components in an integrated system generating from different sources of renewable energy [24]. A generic 12-volt lead–acid battery with 1 kWh of energy storage is proposed to ensure highly reliable performance and cost-effective operation [25]. Specifications are given in Table 4. The capital, replacement, maintenance, and life of the battery are taken as $154, $154, $15.40/year, and 10 years, respectively [19].

Table 4. Properties of generic 1 kWh lead–acid battery [20].

Sl.No	Properties	Ratings
1	Nominal voltage	12 V
2	Round trip efficiency	80%
3	Lifetime throughput	800 kWh
4	Maximum charging current	16.67 A
5	Maximum discharge current	24.33 A

2.4.5. Converter

A generic system converter is proposed to rectify the AC output of the generator to DC, which is much cheaper than a bidirectional converter. Selecting the HOMER (Homer Energy, CO, USA) optimizer allows the HOMER model to optimize the size of the converter. The capital, replacement, maintenance, life, and efficiency of the converter are taken as $154, $154, $15.40/year, 15 years, and 90%, respectively [24].

2.4.6. Controller

A load following (LF) controller is selected because it will produce only enough power to meet the demand. The capital, replacement, maintenance, and life of the controller are taken as $200, $200, $5.00/year, and 25 years, respectively.

2.5. Optimising the Design

For the feasibility study presented in this paper, an industry-recognized simulation software called HOMER Pro® (hybrid optimization of multiple electric renewables) is used. The HOMER Pro® microgrid software has become a recognized global standard for optimizing microgrid design in all sectors, from off-grid village power and island utilities to grid-connected campuses and military bases [26].

2.6. Feasibility Analysis

In terms of financial viability, there are two main parameters. The net present cost (NPC) of a system is the total cost of the system (such as capital costs, replacement costs, operation and maintenance costs, etc.) minus all the revenue during its lifetime. The levelized cost of energy (COE) is the average cost of production of 1 kWh of electricity. HOMER software includes an economic analysis module, so is used to estimated NPC and COE. The lowest possible NPC and COE is desirable [24].

3. Results and Discussions

In this section, different designs, in terms of required turbines at the selected Foveaux site for providing the electricity for the demand of Stewart Island, are compared.

By way of background, the SIESA load profile will be discussed first. The peak hourly load is 209 kW. HOMER software (as explained in Sections 2.5 and 2.6) is used to plot the average hourly and monthly load, as shown in Figure 12. The left graph shows that the average daily load fluctuates between 106 and 209 kW. The right graph shows the load for different months of the year. The minimum load fluctuates between 88 and 174 kW in August, and the maximum load fluctuates between 106 and 209 kW in January. The daily demand for the year averages 3452.9 kWh/d, with a load factor of 0.69. The total demand is 1,260,332 kWh/year.

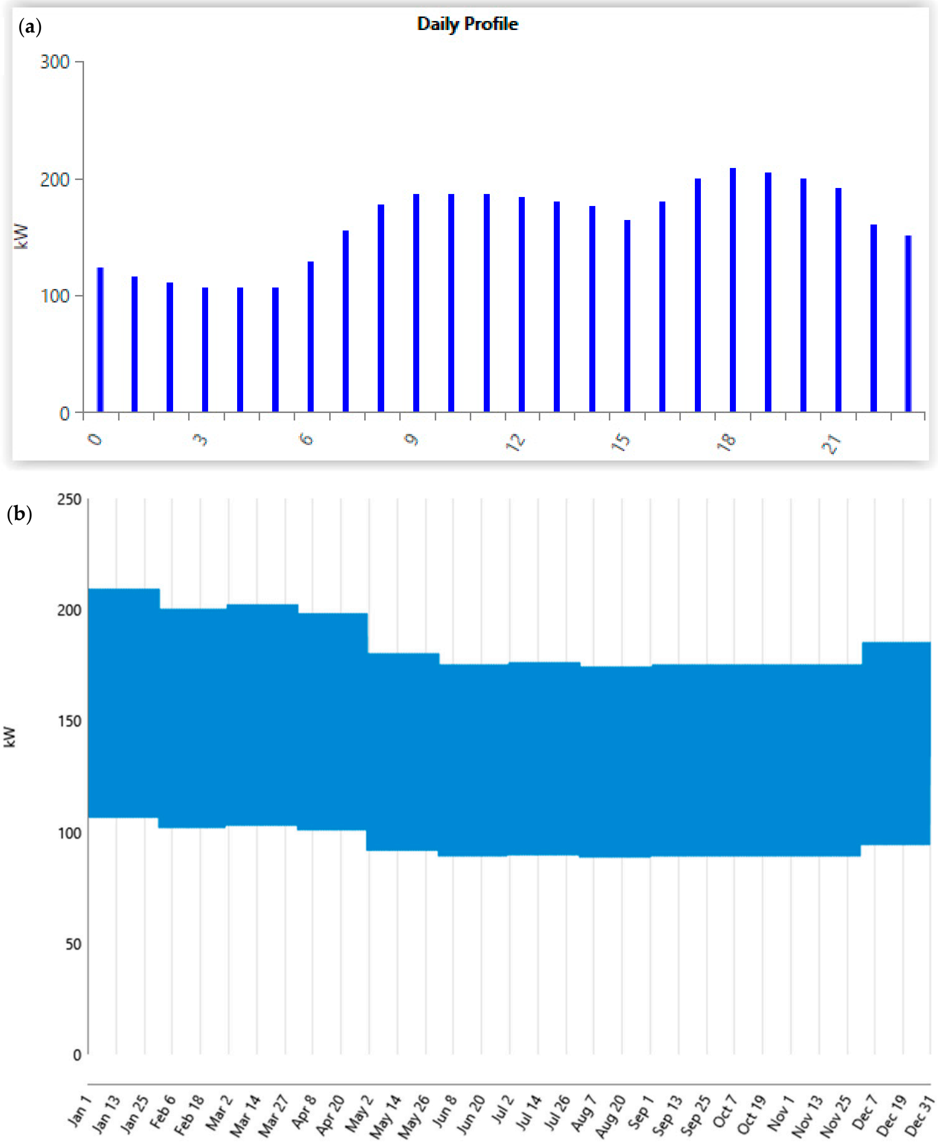


Figure 12. The daily (**a**) and monthly (**b**) load of Stewart Island.

The power that can be output by single wind and tidal turbines at the Foveaux site are shown in Figure 13. The maximum outputs of the selected wind and tidal turbines are 100 kW and 39.3 kW, respectively.

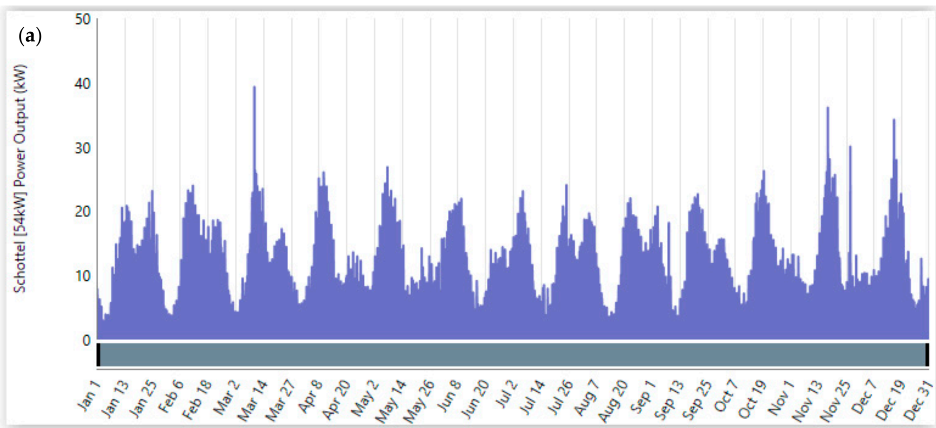


Figure 13. *Cont.*

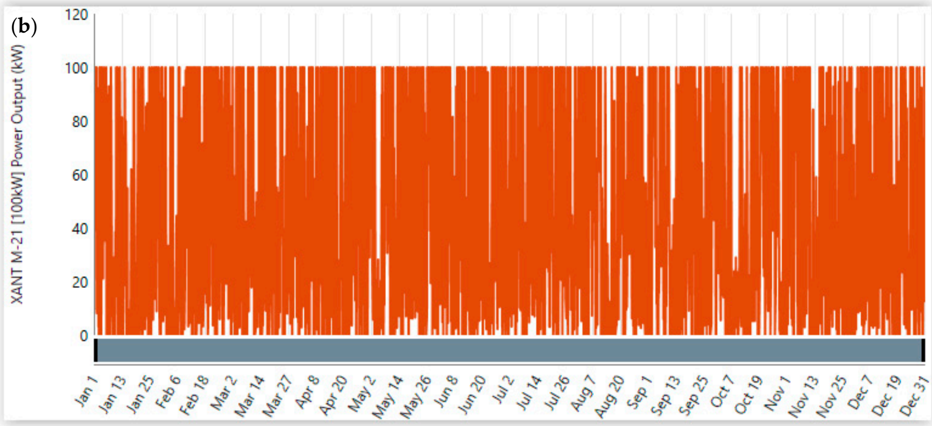


Figure 13. Power output fluctuation for (**a**) tidal turbine and (**b**) wind turbine at the Foveaux site.

Figure 14 compares the fluctuations in power demand for three days, with outputs obtained from a tidal turbine, a wind turbine, and a diesel generator. The red curve represents the overall power generated by the system, while the green one shows the demand. The curves show that more than one wind turbine and more than one tidal turbine would have to be configured, in a hybrid system, to reduce Stewart Island 's dependence on a diesel generator to meet its power demand.

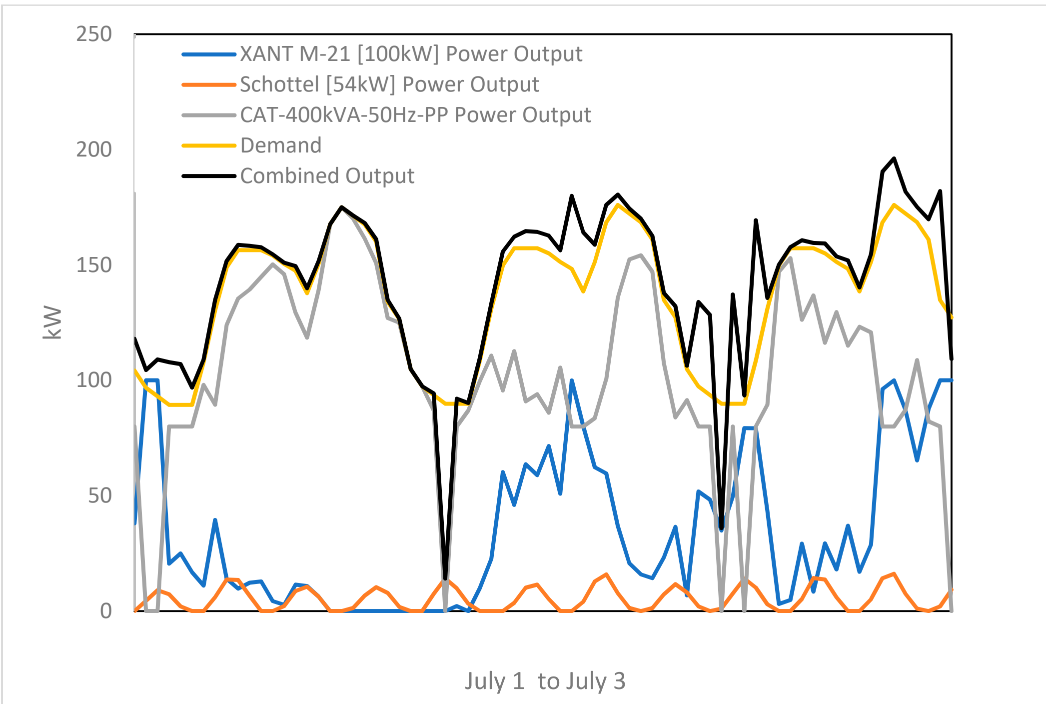


Figure 14. Variation in generated powers and required demand during a three-day period at Foveaux.

In view of what Figure 14 shows, Sections 3.1 and 3.2 evaluate different designs, using HOMER software (Sections 2.5 and 2.6) to optimize turbine and generator operation, so as to meet the fluctuations in demand through the year. The scenarios, in terms of the number of wind (W) and tidal (T) turbines and diesel generators (G), are 1W + 1T, 1W + 2T, 2W + 2T, 2W + 4T and 1W + 10T. Sections 3.3 and 3.4 discuss the results, in terms of power generation and cost-effectiveness, respectively.

3.1. Power Generation Results

Table 5 shows the mean output, hours of operation, and total production for each scenario. Increasing the number of wind and tidal turbines, decreases the hours of operation and the total production from diesel generators. The total power production for all scenarios exceeds Stewart Island's demand (1,260,332 kWh/year).

Table 5. Annual mean output, hours of operation, and power production for proposed scenarios at Foveaux site.

Parameter	1W + 1T	1W + 2T	2W + 2T	2W + 4T
Mean output of W (kW)	45.3	45.3	90.5	90.5
Mean output of T (kW)	4.5	8.9	8.9	17.9
Mean output of G (kW)	111.0	109.0	111.0	109.0
Operation hours of W (h/year)	7747	7747	7747	7747
Operation hours of T (h/year)	5759	5759	5759	5759
Operation hours of G (h/year)	7966	7835	4887	4519
Power production of W (kWh/year)	396,392	396,392	792,785	792,785
Power production of T (kWh/year)	39,124	78,248	78,248	156,495
Power production of G (kWh/year)	880,263	850,602	540,402	490,358
Total Production (kWh/year)	1,315,779	1,325,242	1,411,434	1,439,638

Figure 15a–d show the monthly average power outputs (kW) for different scenarios. Wind energy can generate a large share of output in the scenarios 2W + 2T and 2W + 4T. Tidal energy just starts to generate a significant share of output in the scenario 2W + 4T. Table 6 shows the total electricity production and the percentages contributed by each energy source. The scenario 2W + 4T enables two thirds of production to be generated from renewable sources.

(a) (b) (c) (d)

Figure 15. Monthly average output power for (**a**) 1W + 1T, (**b**) 1W + 2T, (**c**) 2W + 2T, (**d**) 2W + 4T.

Table 6. Share of wind and tidal turbines in electricity production.

Scenario	Total Electricity Production (kWh/year)	Share of Tidal Turbines	Share of Wind Turbine	Share of Generator
1W + 1T	1,315,779	3.0%	30.1%	66.9%
1W + 2T	1,325,242	5.9%	29.9%	64.2%
2W + 2T	1,411,434	5.5%	56.2%	38.3%
2W + 4T	1,439,638	10.9%	55.1%	34.1%

Figure 16 and Table 7 show a possible alternative scenario, 1W + 10T, which might enable a tidal source to contribute as much renewable energy as a wind source. The mean output of wind and tidal turbines are 45.3 and 44.7 kW, and wind and tidal electricity production are 396,392 and 391,238 kWh/year, respectively.

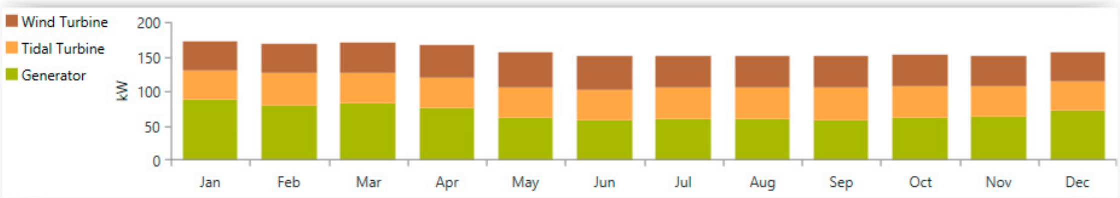


Figure 16. Monthly average output power for 1W + 10T.

Table 7. Share of wind and tidal turbines in electricity production for 1W + 10T.

Scenario	Total Electricity Production (kWh/year)	Share of Tidal Turbines	Share of Wind Turbine	Share of Generator
1W + 10T	1,383,325	28.3%	28.7%	43.0%

3.2. *Financial Analysis Results*

Table 8 is a summary of financial analyses for different scenarios at the Foveaux site.

Table 8. Financial analysis results for different scenarios.

Scenario	Capital (k$)	Fuel Cost (M$)	Operating Cost (k$)	Total NPC (M$)	Levelized Cost ($/kWh)
1W + 1T	350	3.3	323	4.53	0.278
1W + 2T	402	3.2	321	4.55	0.279
2W + 2T	484	2.0	225	3.39	0.208
2W + 4T	593	1.8	222	3.47	0.213

The 2W + 2T and 2W + 4T scenarios seem more economic to install and operate. To show why, Table 9 depicts the optimization results for each scenario. Their renewable fractions are 30.2%, 32.5%, 57.1% and 61.1%, respectively. A renewable fraction of 61.1% means that 61.1% of the electricity is supplied from the wind and tidal turbines, and the rest of it from the diesel generator. Hybrid systems with a renewable fraction of more than 66% are high revenue. [27]. The scenarios 2W + 2T and 2W + 4T almost meet this criterion. They have a lower operating cost, fuel cost, and NPC than 1W + 1T or 1W + 2T. Most importantly, they have a lower COE.

Table 9. Optimization results for (**a**) 1W + 1T, (**b**) 1W + 2T, (**c**) 2W + 2T, (**d**) 2W + 4T.

(**a**)

Architecture						Cost				
Wind Turbine	Generator (kW)	Battery	Tidal Turbine	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)
1	320	407	1	155	LF	$0.278	$4.53M	$323,222	$350,707	30.2

(**b**)

Architecture						Cost				
Wind Turbine	Generator (kW)	Battery	Tidal Turbine	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)
1	320	395	2	155	LF	$0.279	$4.55M	$320,879	$402,914	32.5

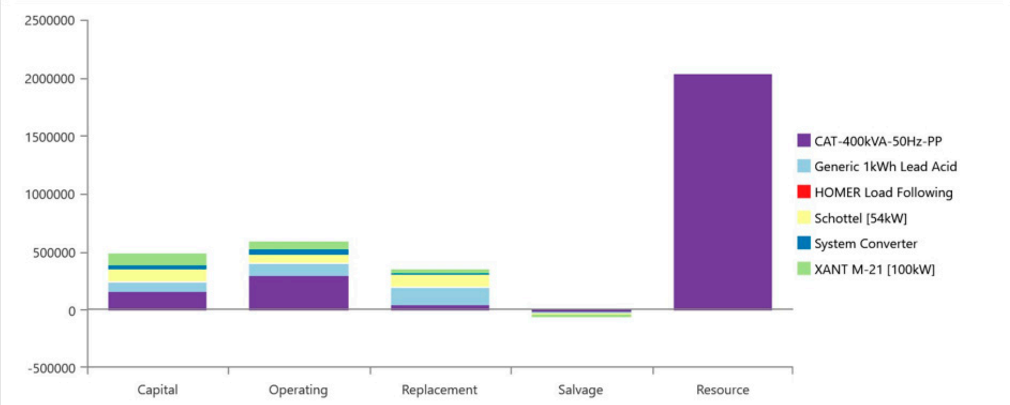
(**c**)

Architecture						Cost				
Wind Turbine	Generator (kW)	Battery	Tidal Turbine	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)
2	320	531	2	222	LF	$0.208	$3.39M	$225,051	$484,103	57.1

(**d**)

Architecture						Cost				
Wind Turbine	Generator (kW)	Battery	Tidal Turbine	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)
2	320	539	4	222	LF	$0.213	$3.47M	$222,234	$593,458	61.1

Figure 17 show the scenario with the lowest costs at the Foveaux site, and the net present cost of each component in the system and the system as a whole. The capital, operating, replacement, and salvage costs are small. The main costs are fuel for the generator and initial construction (no provision to enter it in HOMER's financial analysis module).



Net Present Costs

Name	Capital	Operating	Replacement	Salvage	Fuel	Total
CAT-400kVA-50Hz-PP	$160,000	$303,249	$44,674	-$19,701	$2.04M	$2.53M
Generic 1kWh Lead Acid	$81,774	$105,713	$159,340	-$8,123	$0.00	$338,704
HOMER Load Following	$200.00	$64.64	$0.00	$0.00	$0.00	$264.64
Schottel [54kW]	$108,000	$69,809	$95,411	-$12,936	$0.00	$260,284
System Converter	$34,129	$44,121	$14,480	-$2,725	$0.00	$90,005
XANT M-21 [100kW]	$100,000	$64,638	$31,881	-$17,967	$0.00	$178,551
System	$484,103	$587,594	$345,786	-$61,453	$2.04M	$3.39M

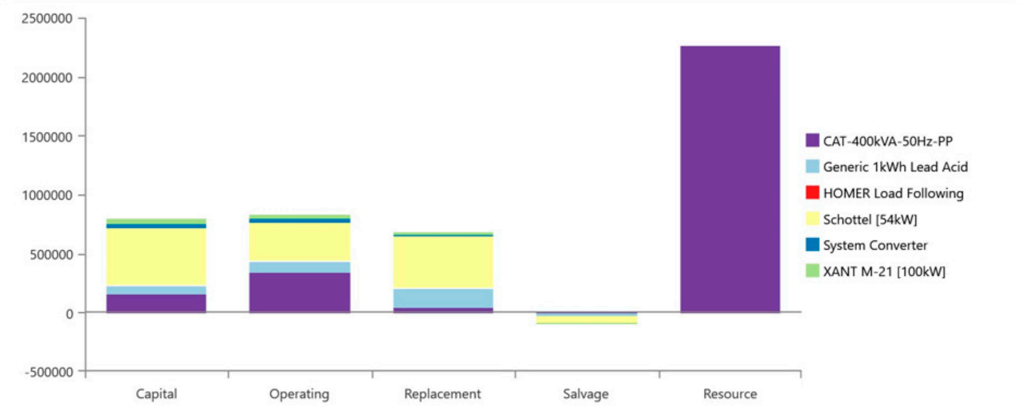
Figure 17. Cost summary and components of scenario with lowest NPC (2W + 2T).

Table 10 depicts the optimization results for a possible alternative scenario that can balance wind and tidal generation, 1W + 10T, which has a renewable fraction of 52.7%. However, the capital cost, operating cost, and NPC are higher than 2W + 2T or 2W + 4T. The COE also becomes higher.

Table 10. Optimization results for balanced alternative scenario 1W + 10T.

Architecture							Cost				
	Wind Turbine	Generator (kW)	Battery	Tidal Turbine	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)
	1	320	449	10	222	LF	$0.275	$4.48M	$284,477	$799,598	52.7

The reason why is shown in Figure 18. Adding more tidal turbines increases the whole-system capital, operating, replacement, and salvage costs. However, it does not reduce the whole-system fuel cost, and the scenario adds to whole-system construction cost (more floating platforms and cables for tidal turbines).



Net Present Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
CAT-400kVA-50Hz-PP	$160,000	$350,470	$51,481	-$13,219	$2.27M	$2.82M
Generic 1kWh Lead Acid	$69,146	$89,389	$164,040	-$12,672	$0.00	$309,903
HOMER Load Following	$200.00	$64.64	$0.00	$0.00	$0.00	$264.64
Schottel [54kW]	$486,000	$314,139	$429,351	-$58,213	$0.00	$1.17M
System Converter	$34,252	$44,280	$14,532	-$2,735	$0.00	$90,329
XANT M-21 [100kW]	$50,000	$32,319	$15,940	-$8,983	$0.00	$89,276
System	$799,598	$830,660	$675,345	-$95,822	$2.27M	$4.48M

Figure 18. Cost and summary results and components of NPC for balanced alternative scenario (1W + 10T).

3.3. Discussion of Power Generation Results

Table 11 shows the mean output power for all the scenarios. Stewart Island's mean power demand is 143.9 kW. All the scenarios can meet the mean demand. Only 2W + 2T's and 2W + 4T 's mean output exceeds the peak demand (209 kW).

Table 11. Mean output for different scenarios.

Parameter	1W + 1T	1W + 2T	2W + 2T	2W + 4T	1W + 10T
Mean Output of Wind Turbine (kW)	45.3	45.3	90.5	90.5	45.3
Mean Output of Tidal Turbines (kW)	4.47	8.9	8.9	17.9	44.7
Mean Output of Generator (kW)	111	109	111	109	105
Total (kW)	160.8	163.2	210.4	217.4	195.0

Table 12 shows the percentage of electricity produced by the wind and tidal turbines. Stewart Island 's total power demand is 1,260,332 kWh/year. The scenario 2W + 4T produces the highest renewable energy fraction, and could contribute 75% of the power demand.

Table 12. Share of wind and tidal turbines in producing electricity and meeting demand.

Parameter	1W + 1T	1W + 2T	2W + 2T	2W + 4T	1W + 10T
Wind Turbine (% of production)	30.1	29.9	56.2	55.1	28.7
Tidal Turbine (% of production)	2.97	5.90	5.54	10.9	28.3
Generator (% of production)	66.9	64.2	38.3	34.1	43.1
Renewable Fraction (% of production)	33.1	35.8	61.7	66.0	57.0
W + T Generated power (kWh)	435,516	474,640	871,033	949,280	787,630
W + T Generated power (% of demand)	34.6	37.7	69.1	75.3	62.5

Table 13 shows the amount of pollutants and fuel consumed. The scenario 2W + 4T is the most environmentally friendly scenario.

Table 13. Emissions of pollutants and fuel consumption.

Parameter	1W + 1T	1W + 2T	2W + 2T	2W + 4T	1W + 10T
Carbon Dioxide (kg/year)	677,709	657,185	415,995	378,894	462,949
Carbon Monoxide (kg/year)	1024	993	629	573	700
Unburned Hydrocarbons (kg/year)	7.70	7.47	4.73	4.31	5.26
Particulate Matter (kg/year)	0	0	0	0	0
Sulfur Dioxide (kg/year)	1684	1633	1034	942	1151
Nitrogen Oxides (kg/year)	3713	3600	2279	2076	2536
Total Fuel Consumed (L)	256,757	248,981	157,604	143,548	175,393
Average Fuel per Hour (L/h)	29.3	28.4	18.0	16.4	20.0

Comparing different designs shows that that 2W + 4T is an optimized hybrid design, which can provide the electricity demand of Stewart Island by using wind, tidal and diesel sources to cover each other during periods when one or another source cannot generate. Further, 2W + 4T's mean output is the highest at 90.5 kW, it can meet the peak load (209 kW), and it can supply 75.3% of Stewart Island's total demand.

In comparison with the optimum scenario, 2W + 2T's mean output is almost as high, and it can also meet the peak load. Its renewable component can still supply 69.1% of the total demand. However, 2W + 2T's diesel consumption is somewhat higher than the optimum scenario, so are its greenhouse gas emissions. The scenarios 1W + 1T and 1W + 2T have a lower mean output, their renewable output cannot meet the peak load, and meet less than 40%. The fuel consumption and emission of pollutants are much higher than other scenarios.

The scenario 1W + 10T can balance wind and tidal power generation. The renewable components can supply 62.5% of the demand. Although less than 69.1% from 2W + 2T and 75.3% from 2W + 4T, this is still a satisfactory renewable fraction.

3.4. Discussion of Financial Analysis Results

In this section, the scenarios are compared, based on the financial analysis results from Section 3.2, which are summarized in Table 14.

Table 14. Financial analysis summary.

Parameter	1W + 1T	1W + 2T	2W + 2T	2W + 4T	1W + 10T
Capital equipment (k$)	350	402	484	593	799
Replacement (k$)	233	282	345	469	675
Construction, End-of-project removal/reinstatement (k$)	-	-	-	-	-
Operating cost (k$)	323	320	225	222	284
Fuel Cost (M$)	3.3	3.2	2.03	1.8	2.2
Total NPC (M$)	4.53	4.55	3.39	3.47	4.48
COE (c/kWh)	0.278	0.279	0.208	0.212	0.274

Capital equipment: The cost is the least for scenarios 1W + 1T and 1W + 2T, but these scenarios do not generate much power from renewable sources. The scenarios that can (2W + 2T, 2W + 4T, 1W + 10T), require higher initial expenditure on equipment purchase;

Replacement: The cost to replace equipment (at the end of design life) is consequently the least for the scenarios that do not generate much renewable power, and is higher for the scenarios that can;

Construction: The cost of project installations is not shown, because HOMER Pro's financial analysis module does not include this. (It just compares equipment, operating and resource costs).

Removal/re-instatement: The cost to remove or re-instate project installations (at the end of design life) is not shown, for the same reason;

Operation: The cost is the least for two scenarios (2W + 2T, 2W + 4T), which generate much power from few turbines. The operating cost for 1W + 10T is greater, because this scenario has numerous turbines. The operating cost is most expensive for the scenarios that do not generate much power from renewable sources. The reason is that the diesel generator (which has a high operating cost) starts up often and runs longer.

Resource: The cost is the least for scenarios that generate much power from wind and tidal turbines (2W + 2T, 2W + 4T, 1W + 10T). The reasons are, firstly, there is no resource cost for wind or tide. Secondly, fuel purchase for the diesel generator is reduced by up to 60%.

The total net present cost of the project (NPC) is the least for 2W + 2T, because this scenario has low equipment and operating costs, and generates much power (62%) from renewable sources, so does not incur a high resource cost. The NPC is almost the same for 2W + 4T, which can generate a greater percentage of power (66%) from renewable sources. However, 1W + 10T, which can still generate much renewable power (57%), is almost as costly as the scenarios that do not, because it requires more expenditure on equipment purchase and operation.

Total cost of energy: The COE is the least for 2W + 2T and almost the same for 2W + 4T, when their NPCs are levelized (per kWh over the life of the project). However, the COE for 1W + 10T, despite its high renewable percentage, is almost as great as the scenarios that do not, once the NPCs of all three are levelized for the purpose of comparison.

The 2W + 4T scenario is optimal for power generation, because it produces the highest renewable fraction (66%), while the RF for 2W + 2T is 62%. Its total NPC seems affordable at 3.47 million dollars. Its levelized cost at 21 c/kWh appears better than the present scenario (5D = 0.23 c/kWh).

A possible alternative scenario, 1W + 10T, would equalize generation from wind and tidal at 28% each, providing a balance of renewable sources. However, its total NPC is considerably higher at 4.48 million dollars, and the levelized cost is also higher at 27 c/kWh.

A problem with HOMER Pro 's financial analysis is that it just evaluates equipment, operating and resource costs, when calculating the NPC and COE. A realistic comparison of NPC and COE should include construction and installation costs, particularly offshore platforms, marine cables, and a DC–AC shore converter station.

4. Conclusions

This paper has proposed the integration of two available offshore renewable energy sources—wind and tidal—using a microgrid, with the aim to decrease the cost of electricity in a remote off-grid coastal community, and avoid the detrimental effects of off-grid diesel generation on the environment.

Stewart Island was selected as a case study because it is typical of isolated coastal communities in New Zealand, which depend on small, locally operated diesel power stations or single-household petrol generators.

Components of a suitable microgrid design were identified as multiple energy sources (wind and tidal turbines, with diesel generators for back-up), storage devices (batteries), supply cables (marine connecting to land), and operating equipment (AC to DC converter, system controller).

An industry-recognized simulation software package, HOMER Pro, was used to optimize the microgrid design, by evaluating scenarios composed of components assembled in different combinations, and to analyze their cost.

The power generation results and financial analysis results for various scenarios, as presented and discussed in Section 3, enable the following several conclusions:

- There is enough tide to generate electricity during 65% of the year at an offshore site close to Stewart Island (referred to as the Foveaux site);
- There is also enough wind to generate electricity during 90% of the year at the Foveaux site. However, this site is on the other site of Foveaux Strait, 40 km away from Stewart Island's community at Oban;
- DC electricity from the offshore Foveaux site can be integrated as a hybrid system with AC electricity from the existing onshore diesel generators at Oban by using a microgrid design, as described in Section 2. The design solution is to mount tidal and wind turbines on the same offshore platform, feed power through a DC marine cable to a DC–AC converter at the Stewart Island shore, then through an AC land cable to a system controller at Oban's diesel generator station;
- The design can be optimised in a way that enables Stewart Island's power to be supplied, in part, from renewable sources. The simulation of various component combinations (in HOMER Pro) shows several scenarios that look promising. The combination that is optimal for maximising renewable generation is two wind and four tidal turbines, plus a single diesel generator;
- The optimal scenario is worth implementing because it could supply 75% of Stewart Island's power demand from renewable sources, reducing the diesel fuel consumption by 60%;
- It is unknown whether the design can be constructed at an affordable cost, because the HOMER Pro financial analysis module does not include construction or installation;
- Once built and installed on site, the design can be operated at an affordable cost, because the levelized cost of equipment and resources over the project life (21 c/kWh) is lower than the present operation cost of five diesel generators (23 c/kWh);
- A complete cost-benefit analysis is needed to find out whether the supply authority can recover all construction, installation, operating and maintenance/replacement costs from a lower charge to the community than its present retail charge (67 c/kWh).

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