

ORIGINAL RESEARCH

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# Increasing wind energy penetration level using pumped hydro storage in island micro-grid system

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## Abstract

Ramea is a small island in southern Newfoundland. Since 2004, it has a wind-diesel hybrid power system to provide power for approximately 600 inhabitants. In this paper, wind speed data, load data, and sizing of pumped hydro system at Ramea, Newfoundland are presented. The dynamic model of wind turbine, pumped hydro system, and diesel generator are included in this paper. The dynamic model is simulated in SIMULINK/MATLAB to determine the system voltage and frequency variation and also to visualize different power outputs. Sizing of pumped hydro system indicates that a 150-kW pumped hydro storage system can be installed in Ramea to increase the renewable energy fraction to 37% which will reduce non-renewable fuel consumption on this island. Also, it is found that a pumped hydro energy storage system for Ramea is a much better choice than a hydrogen energy storage system. Such a system will have a higher overall efficiency and could be maintained using local technical expertise, therefore, a more appropriate technology for Ramea.

**Keywords:** HOMER, Hybrid, Electrolyzer, Pumped hydro

## Background

In the early nineteenth century, settlers formed several small independent communities on the Ramea Islands. In the early 1940s, all inhabitants moved to Northwest Island and formed the Town of Ramea, which was incorporated in 1951. It has a population of 674, and the location provides an excellent harbor and was strategic for exploiting the fishery that was closed recently. Access to the community is through a paved road and by a ferry that runs from Burgeo to Ramea. The nearest community is Burgeo which is about 20 km. Residents of Ramea use furnace oil and wood to heat their homes in the winter. There are 335 customers of the diesel-generated electricity in Ramea. Community average load is 650 kW. The diesel plant uses about 18,000 L/week in the summer, but this could go as high as 22,000/week in the winter. Electricity is sold at \$0.1495/unit. About 30 to 40 cars come and leave the island every day. Five 10,000-L oil tankers bring in diesel for the plant and furnace oil for the community every week. Until recently, a

2,775-kW diesel-generating plant and six 65-kW wind turbines were used to supply power to the town. Figure 1 shows location of the wind turbines on Ramea Island.

The distance between the six old 65-kW wind turbines and three new 100-kW wind turbines is about 2 km. Hydrogen energy storage system is next to the diesel plant. Figure 2 shows the single line diagram for Ramea distribution system.

Three Caterpillar D3512 diesel engines (Peoria, IL, USA) are the main power source of the isolated wind-diesel power plant [1]. Diesel generators are with the following specifications: 4.16 kV, 1,200 rpm, and 925 kW with a power factor of about 0.85. Each of the diesel units (CAT 3512, 1,400-hp engine with a 925-kW generator) is equipped with an automatic voltage regulator and a governor system. Two frequency control modes are used including (1) a speed-droop characteristic for fast load following capability and (2) an isochronous mode for load sharing and frequency regulation. One or two of the three diesel generators are normally required to supply the local community load. Parallel operation and cycling periods of the diesel generators are coordinated by the diesel generator's master controller. The

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Figure 1 Location of wind turbines and diesel plant in Ramea.

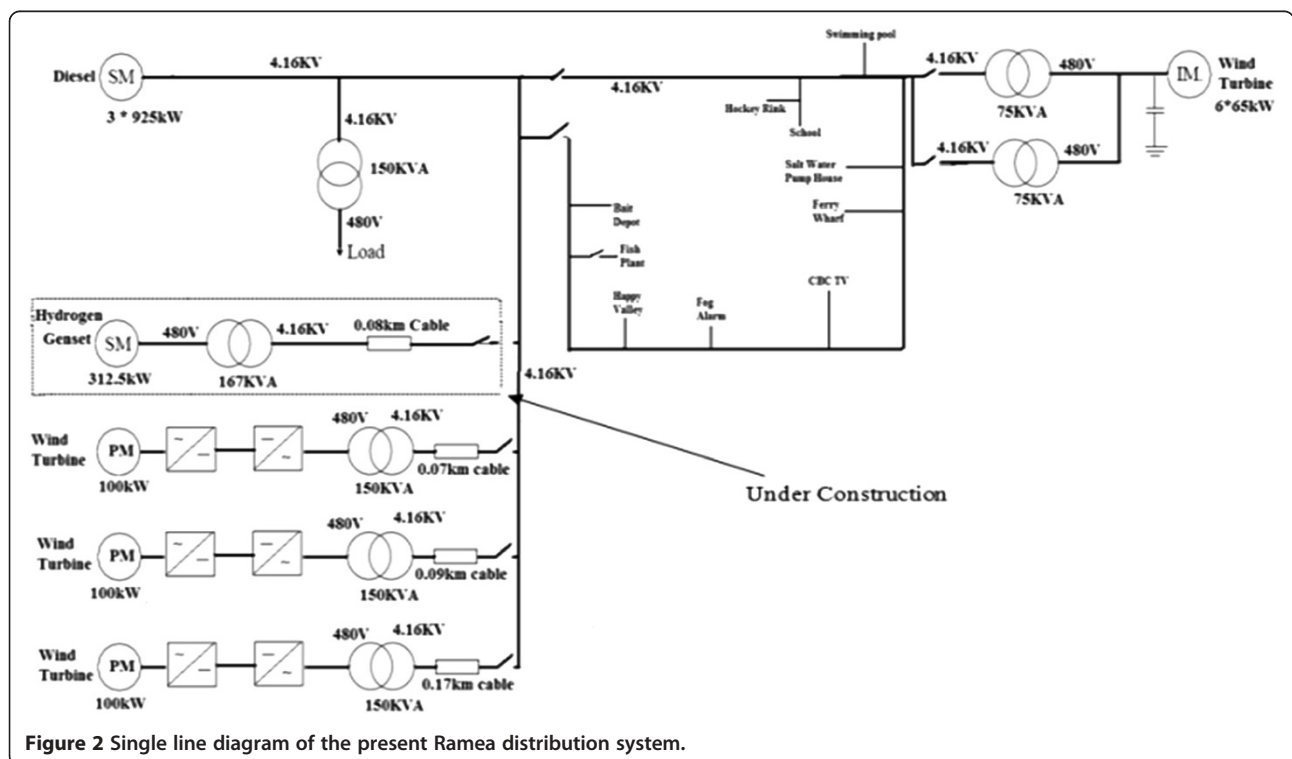


Figure 2 Single line diagram of the present Ramea distribution system.

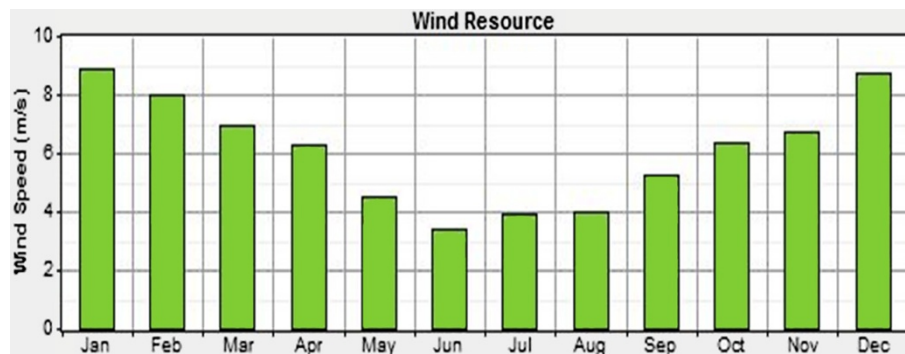


Figure 3 Annual wind speed data of Ramea.

wind energy system consists of six Windmatic wind turbines (OR, USA), a 200-kW controllable dump load, and six capacitor banks. The Windmatic WM15S is a horizontal axis, two-speed, upwind turbine which uses two induction generators, a 65-kW and a 13-kW unit for the energy conversion and direct connection to the distribution system. A 30-kvar fixed capacitor bank is connected in parallel with the output of each wind turbine to partially compensate for the reactive power needs of the induction generators. The start-up of the 65-kW wind turbines is currently assisted by the diesel plants; each wind turbine operates as a motor until it is accelerated beyond synchronous speed, at which point it begins to generate power. The diesel plant also provides the balance of the reactive power, while the capacitor banks are switched on/off to correct the wind plant's power factor to above 0.9.

Annual average wind speed at 10 m in height in Ramea is about 6.08 m/s. This report presents an overview of present pump hydro storage facilities in the world. Analysis of the present wind diesel hydrogen hybrid power system is included. A new pumped hydro storage system is proposed for the community. Based on the recent load and wind data, sizing of a pumped hydro storage (PHS) system is presented. For sizing and analysis, the National Renewable Energy Lab software called HOMER [2] is used. After determining the size of the PHS, the dynamic modeling and simulation of the PHS were carried out to determine the expected system voltage and frequency variations. System design and analysis is presented along with some future policy suggestions. Several studies and simulation have been carried out on pumped hydro storage system [3-7] in the past years.

### Analysis of existing Ramea wind-diesel-hydrogen system

The new Ramea wind diesel hydrogen system is still under construction. In 2009, we visited the site and collected the

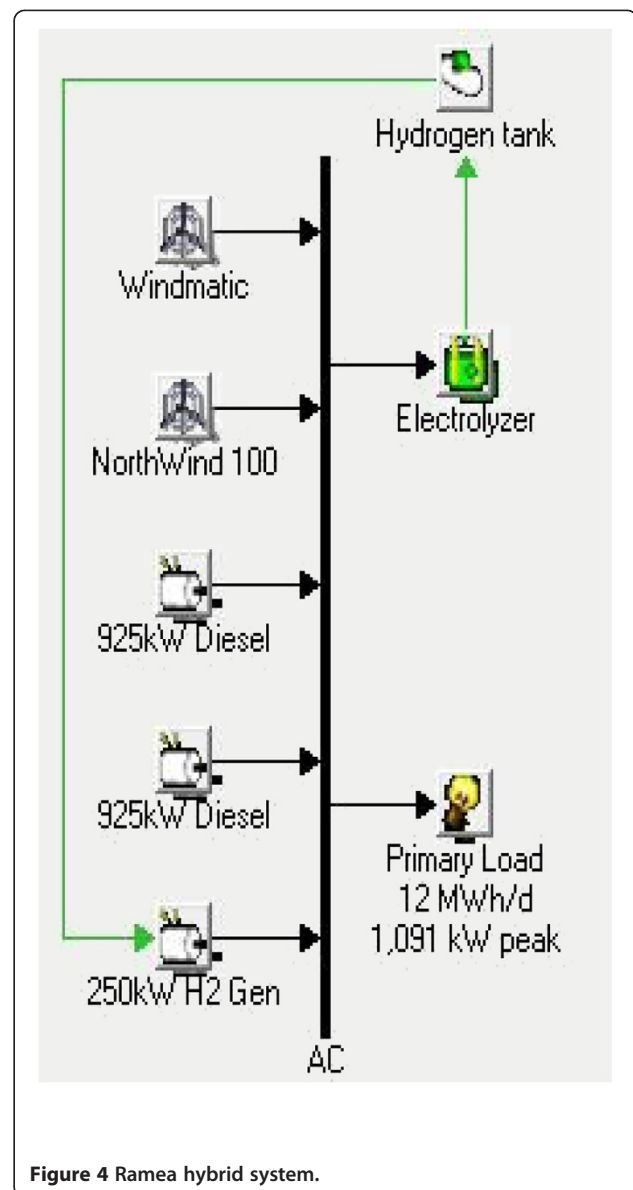


Figure 4 Ramea hybrid system.

site and system data. An analysis of the current configuration of Ramea hybrid system was done using HOMER.

Annual wind speed data for Ramea is shown in Figure 3. The purpose of this analysis is to determine the expected performance of the system. All system parameters and costs were obtained from NL Hydro (St. John's, Newfoundland and Labrador, Canada).

The inputs to HOMER are wind speed data, load data, wind turbine characteristic curve, electrolyzer and hydrogen storage details, hydrogen engine data, turbine costs, and system constraints. The data used in this research was collected from NL Hydro and Environment Canada [8]. From the wind speed data, it is found that the annual average wind speed is about 6.08 m/s at 10 m in height which indicates that this area has one of the highest wind resource regions in Canada. The maximum wind speed is 21.6 m/s. Winter months are windy as compared to summer months. The average wind speed in December and in January is 9 m/s. Community power requirement is also highest during the winter months. It means that using wind energy to reduce diesel consumption makes sense. Figure 4 shows the under construction wind-diesel-fuel cell hybrid power system in Ramea.

The electrical load profile of Ramea is shown in Figure 5. Daily profile indicates that load varies from 350 to 610 kW every day. Monthly profile indicates higher electrical load during the winter months than the summer months in a year.

Load profile also indicates that for a few days in winter, the load may be as high as 1,100 kW. The diesel plant has its own diesel storage tank, and it is also linked to a nearby larger storage tank maintained by a local oil supplier. Ever rising fuel cost is a major issue for Ramea.

Community survival depends upon low cost energy. The simulated hybrid energy system is shown in Figure 6.

Figure 4 shows the current Ramea hybrid power system as simulated in HOMER. It has only an alternating current (AC) bus.

Excess electricity from the wind turbines is converted to hydrogen using an electrolyzer. Hydrogen is compressed and stored in three large tanks. Stored hydrogen is used to generate electricity when needed. All system parameters including costs were obtained from NL Hydro. System expected performance was analysed, and it is presented in Figure 5. It shows that the expected renewable fraction is 37% and the cost of electricity would be \$0.248/unit. One 925-kW diesel is always running. A second diesel would be needed only for 12 h in a year. A hydrogen generator will run only for 702 h in a year. Expected electrical performance is shown in Figure 5. It shows that the hydrogen generator will contribute only 1% of electricity to the system, while the electrolyzer will consume 10% of the system electricity. In other words, most of the electricity taken by the electrolyzer will be wasted in the system.

### Sizing of a pumped hydro storage system

Sizing of the hybrid power system was done with the help of the optimization software HOMER. The hydrogen energy storage system shown in Figure 7 was removed, and it was replaced with a battery model in HOMER. Overall efficiency of the battery was reduced to 70% to represent a pumped hydro energy storage system. (Typical efficiency of a pumped hydro system is 70%). HOMER sized the system by making energy balance calculations for each of the 8,760 h in a year. Simulated hybrid energy system electrical performance is shown in Figure 8.

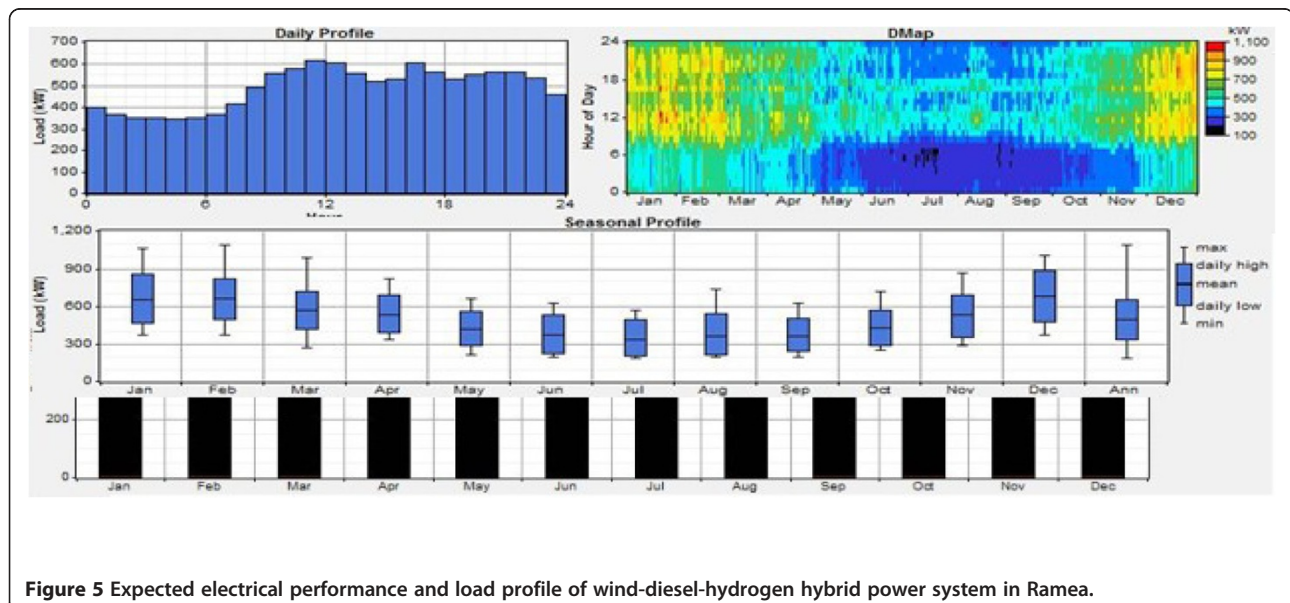


Figure 5 Expected electrical performance and load profile of wind-diesel-hydrogen hybrid power system in Ramea.

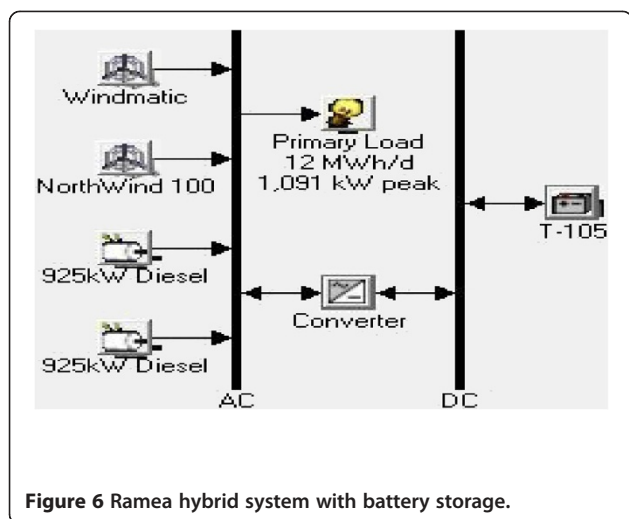


Figure 6 Ramea hybrid system with battery storage.

For each hour, HOMER compares the electric demand in the hour to the energy that the system can supply in that hour and calculates the flows of energy to and from each component of the system. The system cost calculations account for costs such as capital, replacement, operation and maintenance, fuel, and interest. In the HOMER simulation, it is assumed that the interest rate is 7% and the project lifetime is 25 years. With a condition of 40% renewable energy fraction, the optimized HOMER simulation results including sensitivity variables are shown in Figure 8. Renewable energy fraction for all cases is about 37%. From Figure 8, it is clear that yearly diesel consumption reduces with the battery size. The larger the battery

sizes, the less diesel consumption. HOMER suggested that the best battery bank (consisting of Trojan T-105 batteries) should have 500 batteries. Based on the maximum power coming out of batteries, we selected a 250-kW converter between AC and DC buses. The nominal capacity of each T-105 battery is 1.35 kW h. Figure 9 describes the expected energy in and out of the battery storage system.

It shows that wind turbine will produce 37% of the total energy while the remaining 63% will come from the diesel plant. Expected diesel consumption is also shown in Figure 8, and it is less than what is shown in Figure 5. Figure 8 shows that most of the electricity will be produced by wind energy during the winter season, and less energy should be expected during the summer season. Therefore, during summer, most of the electricity demand will be met from the diesel. Figure 8 also shows that the total electrical energy required for that area is 4,281,096 kW h/year, and 37% of that will be met by the wind energy including the system peak demand. Figure 8 shows the monthly statistics and expected frequency histogram of battery state of charge. On average, the battery will be 70% charged (i.e., upper reservoir will be 70% full). The battery will be most used in July and August, while it will be least used in May. Effectively, this battery represents a pump hydro energy storage system with an overall efficiency of 70%. During our visit to Ramea in September 2009, we looked for small ponds or lakes which can be used for a pumped hydro installation. We found two small ponds whose elevation is a few meters above sea level. A head of few meters is not good for a pump hydro installation. The hills in Ramea can be used for such a purpose.

Sensitivity variables

Primary Load (kWh/d) 11.72% Wind Speed (m/s) 6.08 Diesel Price (\$/L) 0.8

Double click on a system below for simulation results.

														Category	Overall	Export	Details
W	N	D925 (kW)	D925 (kW)	T-105	Conv. (kW)	Initial Capital	Operating Cost (\$/yr)	Total NPC	COE \$/kW	Ren. Frac.	Diesel (L)	D925 (hrs)	D925 (hrs)	Batt Lf (yr)			
6	3	925	925	500	250	\$2,515,000	717,349	\$10,874,687	0.218	0.37	783,529	7,406	4	6.3			
6	3	925	925	400	250	\$2,494,000	719,809	\$10,882,348	0.218	0.37	790,927	7,497	3	6.9			
6	3	925	925	600	250	\$2,536,000	716,421	\$10,884,867	0.218	0.37	779,219	7,353	5	6.3			
6	3	925	925	700	250	\$2,557,000	715,555	\$10,895,774	0.218	0.37	776,015	7,314	4	6.5			
6	3	925	925	300	250	\$2,473,000	723,931	\$10,909,385	0.219	0.36	800,916	7,619	4	8.8			
6	3	925	925	800	250	\$2,578,000	714,937	\$10,909,582	0.219	0.37	773,429	7,283	2	6.8			
6	3	925	925	900	250	\$2,599,000	713,855	\$10,917,965	0.219	0.37	770,929	7,252	3	7.2			
6	3	925	925	1000	250	\$2,620,000	713,220	\$10,931,568	0.219	0.37	769,292	7,232	3	7.6			
6	3	925	925	1100	250	\$2,641,000	711,971	\$10,938,014	0.219	0.37	767,470	7,210	2	8.1			
6	3	925	925	1200	250	\$2,662,000	711,365	\$10,951,948	0.220	0.37	766,244	7,195	2	8.6			
6	3	925	925	1300	250	\$2,683,000	710,431	\$10,962,066	0.220	0.37	764,807	7,177	3	9.1			
6	3	925	925	1400	250	\$2,704,000	709,815	\$10,975,885	0.220	0.37	763,798	7,164	5	9.5			
6	3	925	925	1500	250	\$2,725,000	709,163	\$10,989,287	0.220	0.38	762,766	7,152	3	10.0			

Figure 7 HOMER-optimized results for the proposed hybrid system.

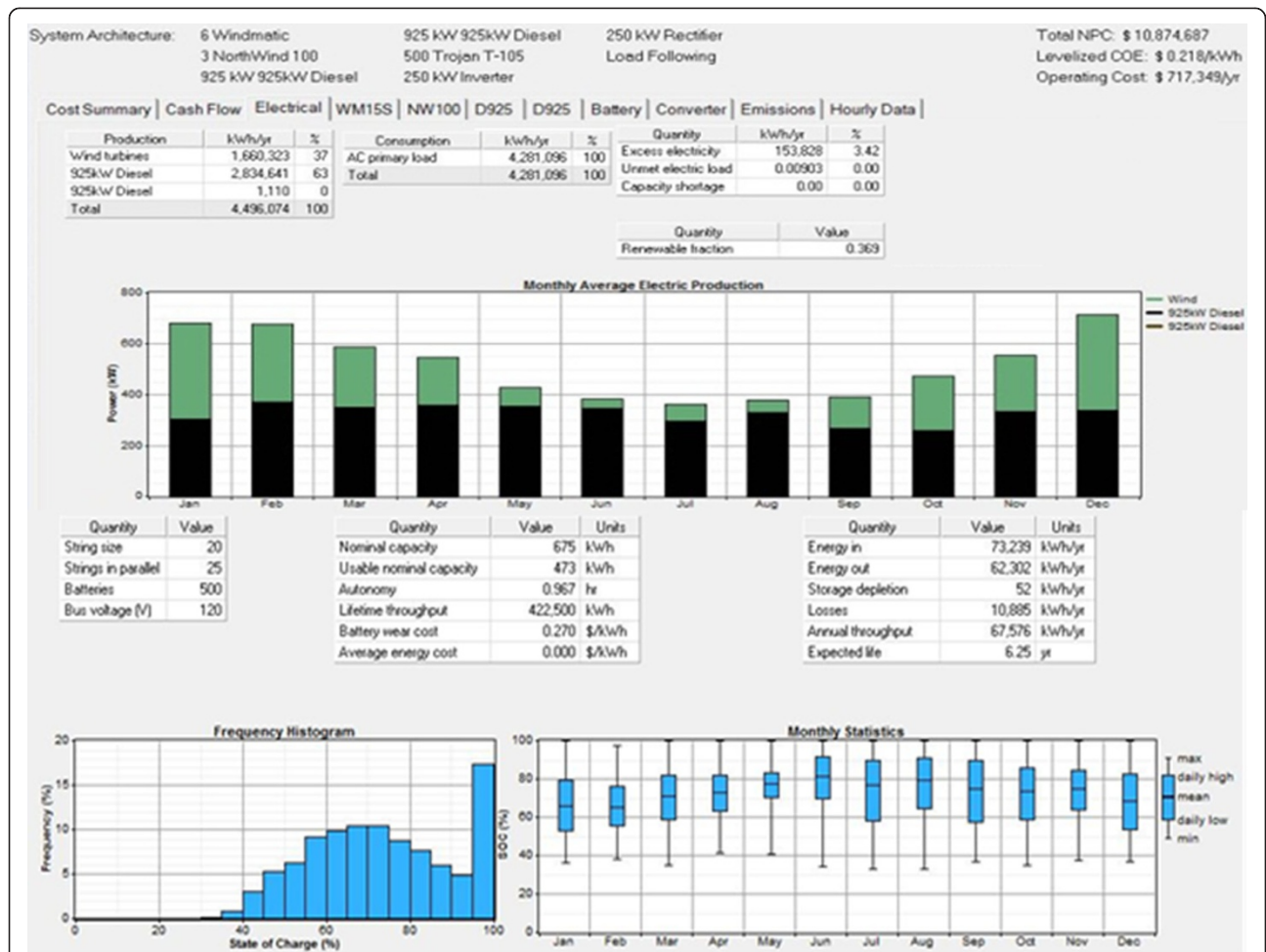


Figure 8 Expected electrical performance of the proposed hybrid power system.

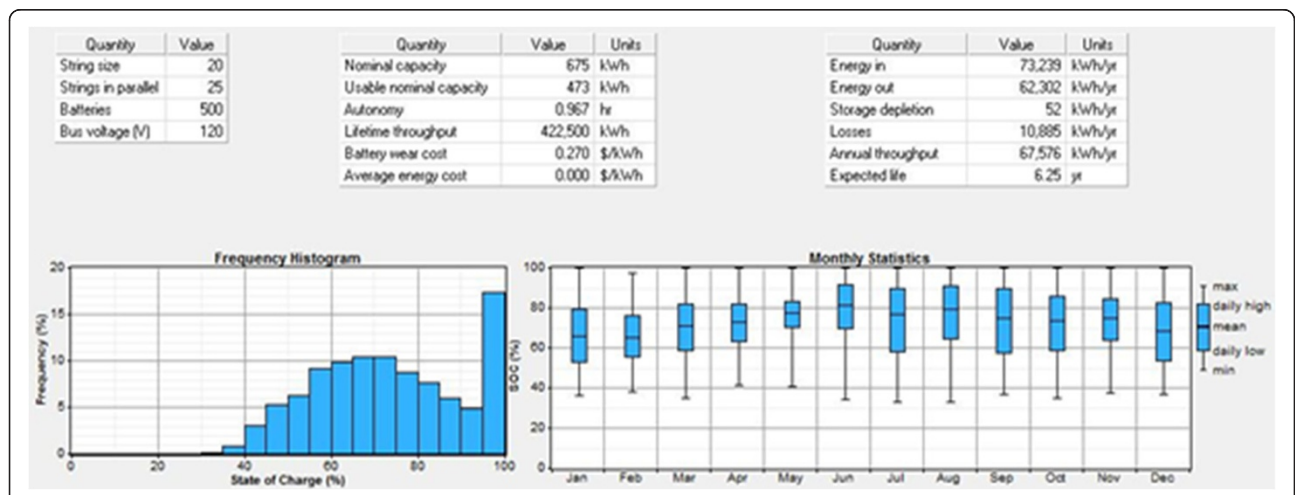


Figure 9 Expected energy in and out of the battery storage system.

It appears that a storage system needs to be built on a hill. In the east side of Ramea, we noted a hill named the Man of War (see Figure 10).

It is a potential place where a hydro reservoir can be built at 63 m in height as shown in Figure 11.

Access to this hill is not an issue as there is a telecommunication tower already installed for the community's communication on the next hill. The Man of War Hill is one of the highest hills in Ramea, and presently, nothing exists there. It has a significant area at the top and is very close to the water, i.e., required length of penstock would be minimal. In a hydro power plant, potential energy of the water is first converted to an equivalent amount of kinetic energy. The potential energy stored in the upper reservoir should be the same as the energy stored in the batteries suggested by HOMER. Figure 8 shows that we will need 500 Trojan T-105 batteries (each 1,350 Wh). Hence, the potential energy stored in the upper reservoir should be as follows:

$$\begin{aligned} \text{Potential energy} &= mgh \rightarrow 1,350 \times 3,600 \times 500 \\ &= mgh = (\text{volume} \times \text{density}) \\ &\quad \times g \times h \rightarrow V = \frac{1,350 \times 3,600 \times 500}{9.81 \times h \times 1,000} \end{aligned}$$

For a head,  $h = 63$  m, required reservoir size will be  $V = 3,932 \text{ m}^3$  (equivalent to 500 batteries). Figure 10 shows the topographical location of Man of War Hill in Ramea. From Figure 10, it can be seen that about 2,000- $\text{m}^2$  area is available to build a hydro storage reservoir.

The height of the reservoir will be 2 m which is a reasonable height for a man-made concrete-based covered pool-type tank. The size of the hydro turbine is determined by observing the output of the converter shown in Figure 12.

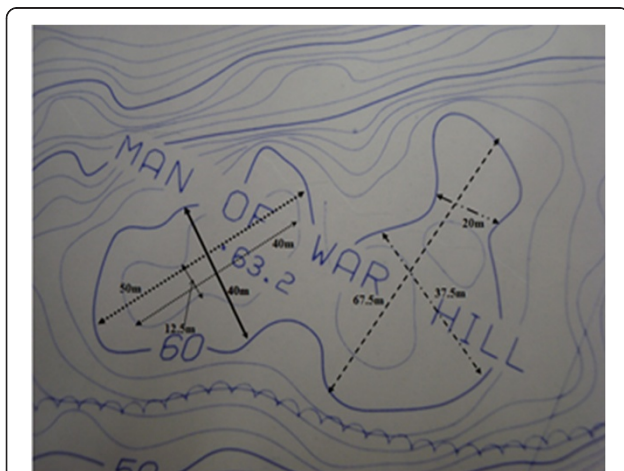


Figure 10 Topographical map of Man of War hill.

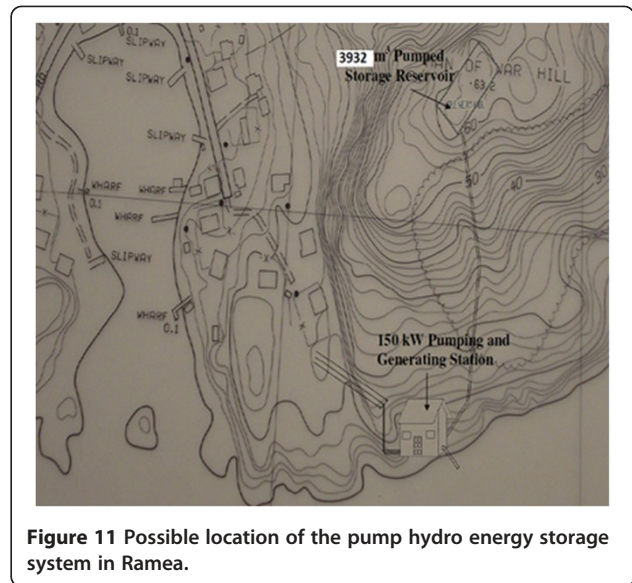


Figure 11 Possible location of the pump hydro energy storage system in Ramea.

From the HOMER time series data, it was found that during April, maximum power flow from the converter is 147 kW. Figure 13 shows expected output of the converter in June.

It shows that we might be taking power from the reservoir for more than 3 h.

### Dynamic simulation of grid-connected PHS

The amount of power available from a micro hydro power system is directly related to the flow rate, head, and the acceleration due to gravity. From the above maximum daily average power of 147 kW to approximately 150 kW, the usable flow rate can be calculated using the equation  $P = \eta \times Q \times H \times g$ . Here,  $P$  = power output in kilowatts (150 kW),  $Q$  = usable flow rate in cubic meter per second,  $H$  = gross head in meters (63 m),  $g = 9.81 \text{ m/s}^2$ , and  $\eta$  = hydro turbine efficiency which is equal to 70%. From the above equation, we determined the flow rate  $Q = 0.347 \text{ m}^3/\text{s}$ . The minimum operating time for the hydro turbine will be equal to  $3,932 \text{ m}^3 / 0.347 \text{ m}^3/\text{s} = 11331 \text{ s} = 3.14 \text{ h}$ . Figure 11 shows a possible site for a pump hydro facility. The proposed pumping and generating station could be about 100 m from the top reservoir and about 60 m from the existing 4.16-kV transmission line.

Hydro electricity generation is considered as an established renewable technology. A water flow from an upper to a lower level represents a hydraulic power potential. Pumped storage plants utilize a reversible pumping turbine to store hydro energy during off-peak electricity hours by pumping water from a lower reservoir to an upper reservoir. This stored energy is then used to generate electricity during peak hours, when electricity is costly to produce, by flowing water from

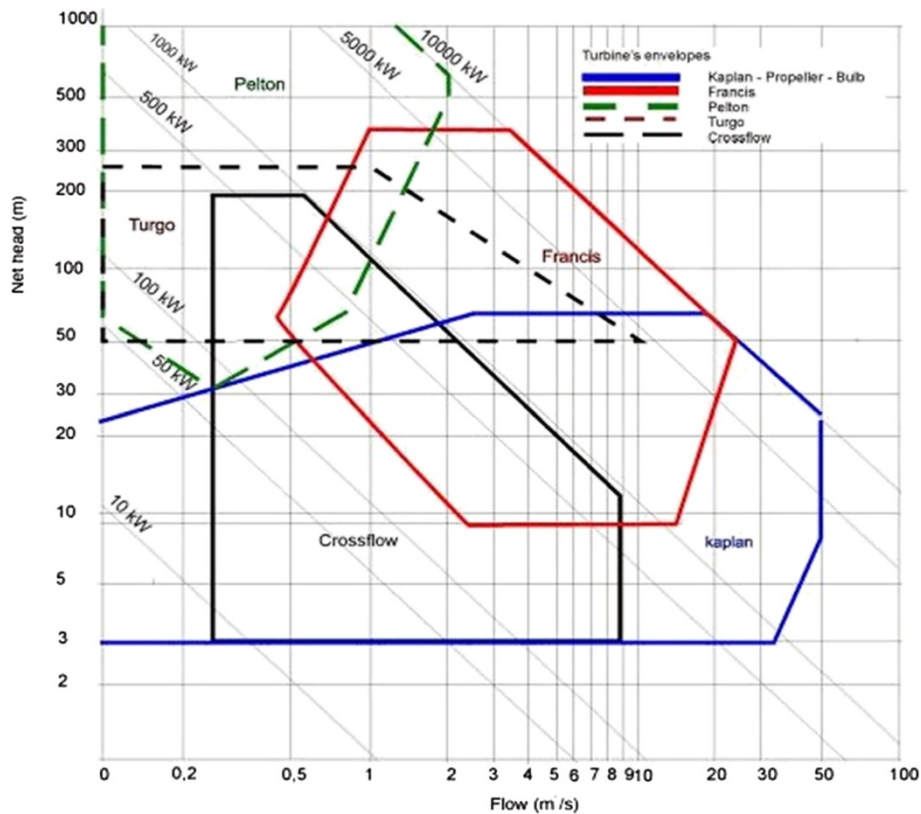


Figure 12 Turbine selection based on head and discharge.

the upper to the lower reservoir. The pumped hydro storage system will store excess energy during the off-peak time which will be produced by six 65-kW wind turbines, three 100-kW wind turbines, and a diesel plant.

The stored energy will be used to produce electricity during peak times throughout the day. Hydro turbines can be broadly categorized into either impulse or reaction turbines. Figure 12 shows a guide for selection of

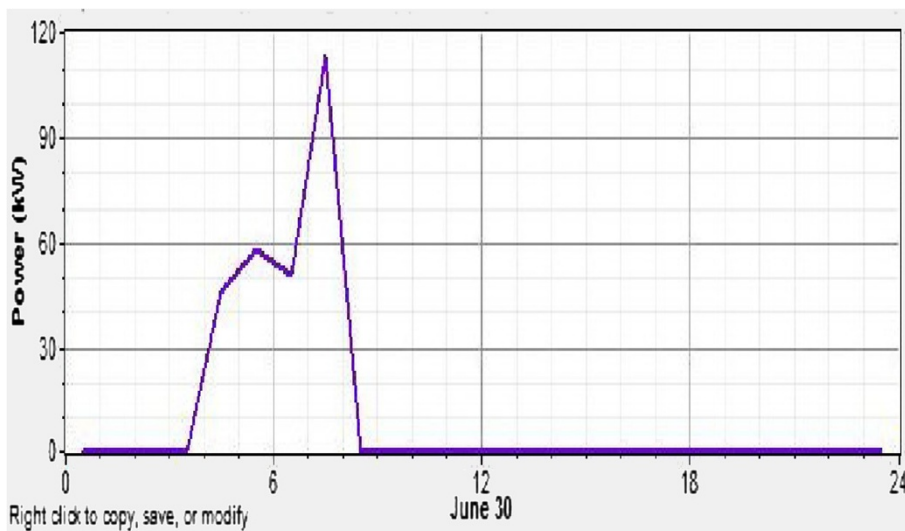


Figure 13 Output of converter in June.



hydro turbine. For the Ramea site, the expected flow rate is  $0.347 \text{ m}^3/\text{s}$ , and head is 63 m; therefore, the best selection from Figure 12 is a pelton- or turgo-type turbine.

The reference sites [9-11] can be used for a selection of turbine for the pumped hydro storage project in Ramea. Dynamic simulations of the proposed Ramea wind-diesel-pumped hydro system were done to determine the expected power quality. Simulation was also done to find out if an addition of a 150-kW pump hydro unit will greatly impact the stability of the system. Figure 14 shows diesel-wind-hydro hybrid power system in Ramea simulated in SIMULINK.

From Figure 8, it can be seen that only one diesel generator is running at a time; that is why dynamic simulations were done, considering only one diesel in the system. Figure 14 shows 390- and 300-kW blocks representing all 65-kW and all 100-kW wind turbines in Ramea, respectively. Here, the pump is considered as a 150-kW centrifugal pump with induction machine, and hydro turbine is considered as a 150-kW unit with a synchronous machine coupled to the system bus. Community load is considered as a constant load, and the system was simulated for 24 s. It took a quad core processor-based computer more than 3 h to complete one 24-s simulation. The system was studied for a varying wind speed.

In order to determine the system voltage and frequency variations, the following equations were used to generate a wind field [12].

$$V_w = V_t + V_a, \frac{dV_t}{dt} = -\frac{1}{T_v} V_t + m_w(t), T_v = \frac{10.5z}{V_o}$$

Here,  $V_w$  is the wind speed, which is composed of the average wind speed component ( $V_a$ ) and turbulence component ( $V_t$ ). The average wind speed value is chosen as 8.02 m/s;  $m_w(t)$  is the random white noise which is used to generate the turbulence component within the wind field. Variable  $z$  is the turbine height, and  $V_o$  is the maiden wind speed. The wind speed characteristics are applied to the simulation, assuming a constant load of 500 kW at Ramea. During our simulation, it is considered that the pumping motor will operate for the first 5 s, and then, it will be switched off. At the 11th second, the hydro turbine will start, and it will operate for 5 s and then will switch off. It is understood that such fast switching will not happen in a real system. In a real system, such switching will happen in tens of minutes. It was not possible to do dynamic simulations for time in minutes. (a 1-min simulation took more than 3 days of computer time. The computer often hangs up, or

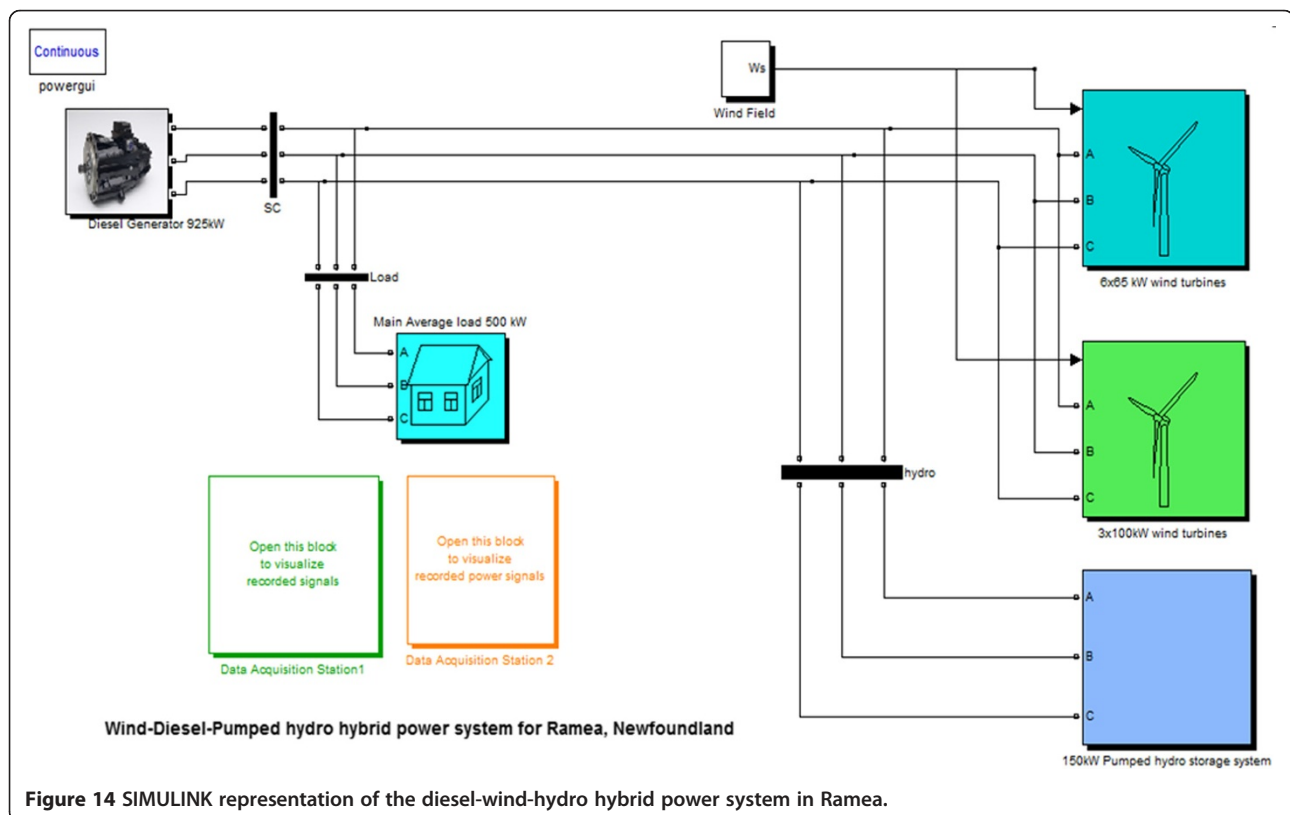


Figure 14 SIMULINK representation of the diesel-wind-hydro hybrid power system in Ramea.

simulation code crashes before simulation is done for 1 min.) Switching after 5 s well represents the transient in the system. Simulation for 24 s gave a good idea of expected transient in the system. Figure 15 shows power variations in the system.

From Figure 16, a voltage dip and a current surge can be seen for the first 5 s when induction motor is running the pump to store water in the upper reservoir.

The diesel engine tried to maintain the power balance by running faster, and the system frequency increased to 61 Hz. At  $t=5$  s, the pump was switched off, and the system came back to its original state within a few seconds. At the 11th second, the hydro turbine is switched on for 5 s. This leads to another transient in the system. Figure 16 also shows the expected variation in the system voltage, frequency, and current during this transient. It can also be noted in Figure 16 that a small

variation in the wind speed is not leading to any significant transient in the system. Figure 15 shows the expected power variation in the system. It can be noted in Figures 15 and 16 that simulation was not perfectly converging between  $t=11$  s and  $t=16$  s. Significant time was spent to resolve this issue, but this remained unresolved. Various methods of integration were tried but all led to similar results.

Figure 15 shows the power output from all wind turbines. Wind plant operation results in fluctuating real and reactive power levels and will result in voltage and current transients. Changes in the mean power production and reactive power needs of a wind turbine can cause a steady state voltage and frequency change in the connected grid system. The voltage and frequency variation at load end is given in Figure 16. From Figure 16, it can be seen that the expected voltage variation and the frequency variation

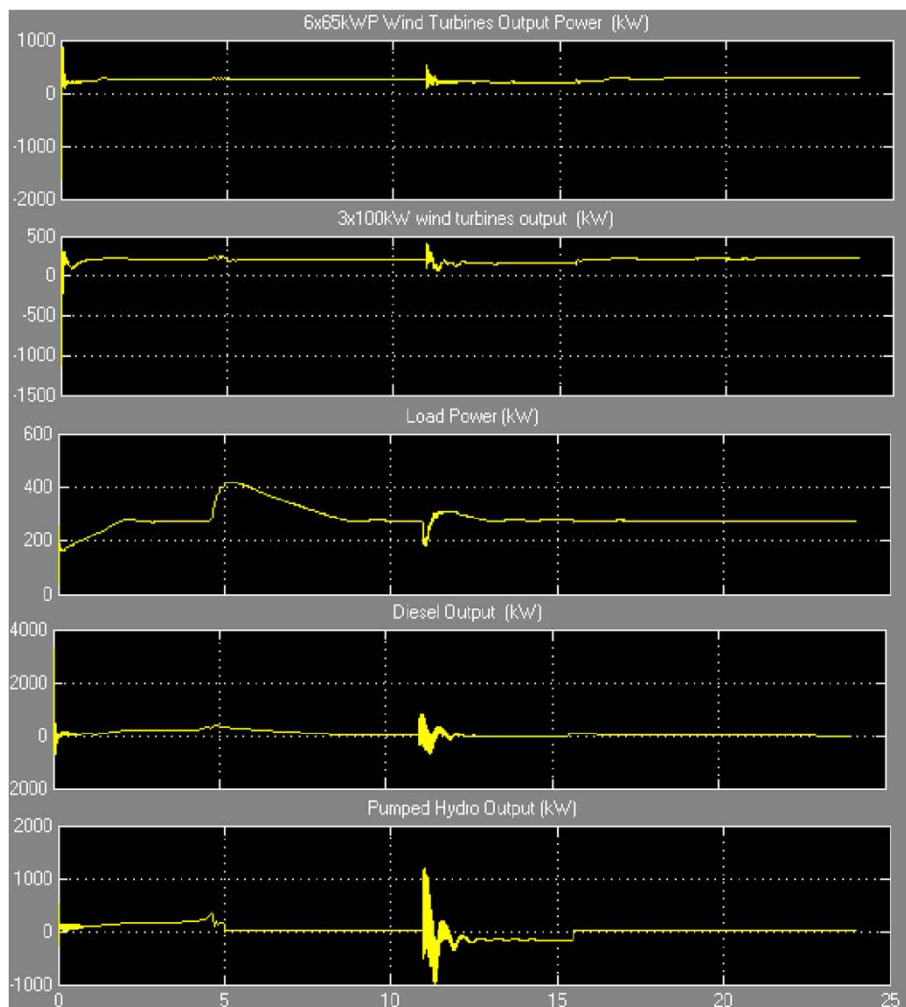
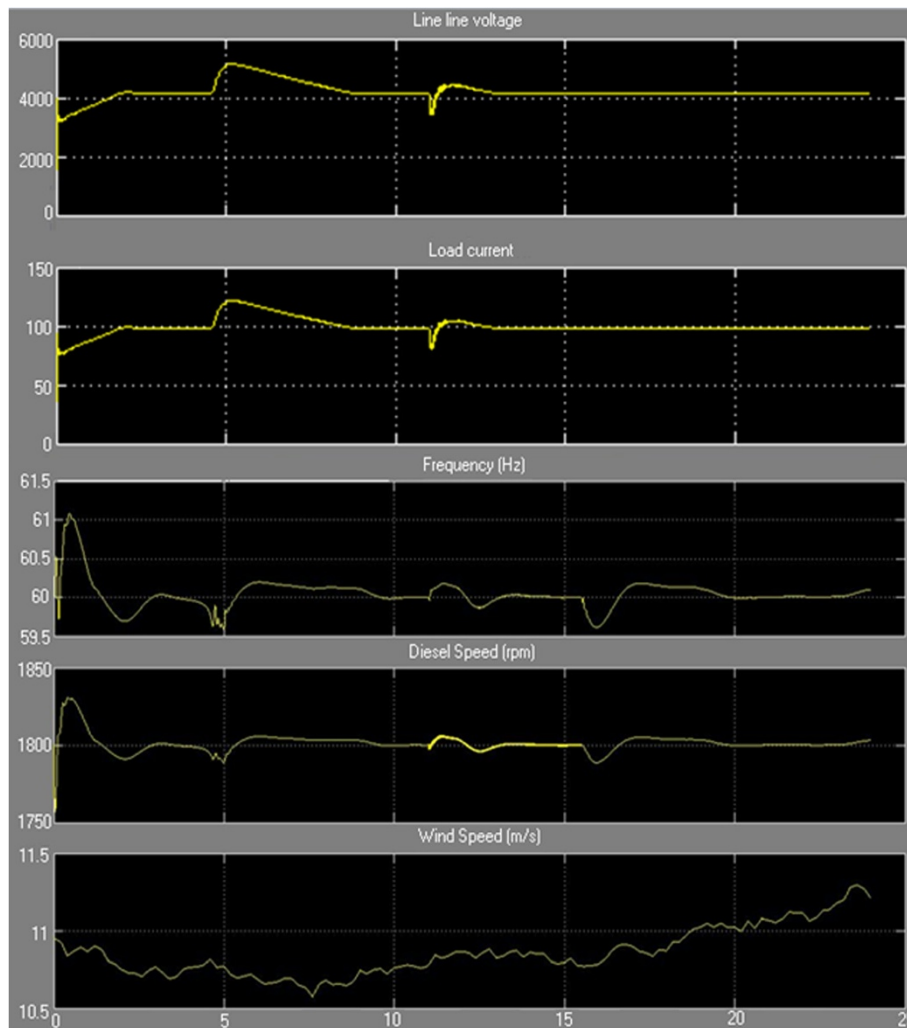


Figure 15 Expected power changes in a transient condition in the Ramea hybrid power system.



**Figure 16** Expected transients in the Ramea hybrid power system.

due to wind speed variation is negligible although switching of large load or a hydro generation unit will cause large voltage and frequency variations in the system. According to power quality standard EN 50160, the voltage variation at the customer's end in remote locations is required to be within +10% [13]. Some voltage variation can be counteracted by adjusting the power factor of the wind turbines [14]. Therefore, the expected voltage and frequency variations in the proposed Ramea wind diesel pump hydro generation system are within current power quality standard.

### Conclusions

The current hybrid power system in Ramea consists of a diesel plant, wind turbines, and a hydrogen-based

energy storage system. Our analysis indicates that yearly contribution from the hydrogen storage to the system will be less than 1%. We propose a pumped hydro based energy storage system for Ramea. Our study shows that a 4000 m<sup>3</sup> water reservoir could be built on the Man of War hill in Ramea for excess wind energy storage. This reservoir will have a head of 63 m and can use sea water. A 150 kW pumping and turbine station could be built near the base of Man of War hill next to the available water and already existing transmission line. Our analysis indicates that such a pumped hydro energy storage system will lead to a 37% renewable energy fraction and will result in acceptable electrical transients in the system. Using a synchronous machine-based turbine unit and an induction motor-based pumping unit, a

pumped hydro energy system can be directly connected to the system. A variable speed system [15] is also a possibility. We believe such an energy storage system can be built and maintained using locally available technology and manpower. Therefore, we recommend a full feasibility study of such an energy storage system for Ramea, Newfoundland. We also believe that pumped hydro energy storage is the best energy storage option for many diesel communities in Newfoundland and Labrador.

#### Competing interests

The author declares that he has no competing interests.

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