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Wind-Diesel Hybrid Power System

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Feasibility Study of Pumped Hydro Energy Storage for Ramea Wind-Diesel Hybrid Power System

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Summary: 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. The average wind energy contribution to the total supplied load is less than 10%. Newfoundland and Labrador Hydro with the support of ACOA has upgraded the Ramea hybrid power system. They have added three more 100kW wind turbines and a hydrogen energy storage system. The new system is still under construction and it is expected to be fully operational by fall 2010. In a hydrogen energy storage system, excess wind generated electricity is converted to hydrogen using a 70% efficient electrolyzer. The hydrogen produced is compressed and stored in tanks. Compressed hydrogen is used to run a less than 35% efficient hydrogen engine as needed. It is expected that overall conversion efficiency of the energy storage system will be less than 25%. For a remote location like Ramea where there are few hills with a height above 60m a pumped hydro energy storage is possible. The overall efficiency of a pumped hydro energy storage system is typically above 70%.

In this research we present a study of a pumped hydro long-term energy storage system for Ramea wind-diesel system. We determined optimal energy storage requirements for the Ramea hybrid power system, identified a site that can be used for pumped hydro energy storage and calculated the required storage capacity. We present a detailed analysis and dynamic simulation of the proposed wind diesel pumped hydro system. Sizing of a pumped hydro system indicates that a 150kW pumped hydro storage system at Ramea can achieve a renewable energy fraction to 37%. Such a system will need a 3932m^3 water reservoir at a height of 63m (on top of Man of War Hill) and it will provide 150kW for 3.14 hours. Dynamic system simulations indicate acceptable power quality after an addition of a pumped hydro storage system.

We think 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.

Introduction:

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 harbour 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 20km. Residents of Ramea use furnace oil and wood to heat their homes in winter. Figures 1 and 2 below show two views of Ramea from Man of War Hill. There are 335 customers of the diesel-generated electricity on Ramea. Community average load is 650kW. The diesel plant uses about 18000L per week in summer but this could as high as 22000L per week in winter. Electricity is sold at \$0.1495 / unit. About 30-40 cars come and leave the island every day. Five 10000L oil tankers bring in diesel for the plant and furnace oil for the community every week.

Figure 1: A view of Ramea showing the community, diesel plant and three recently installed 100kW wind turbines

Figure 2: A view of Ramea showing six, 65kW wind turbines and community water tank.

Until recently a 2775kW diesel generating plant and six, 65kW wind turbines were used to supply power to the town. Three Caterpillar D3512 diesel engines are the main power source of the isolated wind-diesel power plant [1]. Diesel generators are 4.16 kV, 1200 rpm and 925 kW with a power factor of about 0.85. Each of the diesel units (CAT 3512, 1400hp engine with a 925kW 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 2 of the 3 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 wind energy system consists of 6 Windmatic wind turbines, a 200-kW controllable dump load, and 6 capacitor banks. The Windmatic WM15S is a horizontal axis, 2-speed, up-wind turbine which uses 2 induction generators, a 65- kW unit 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.

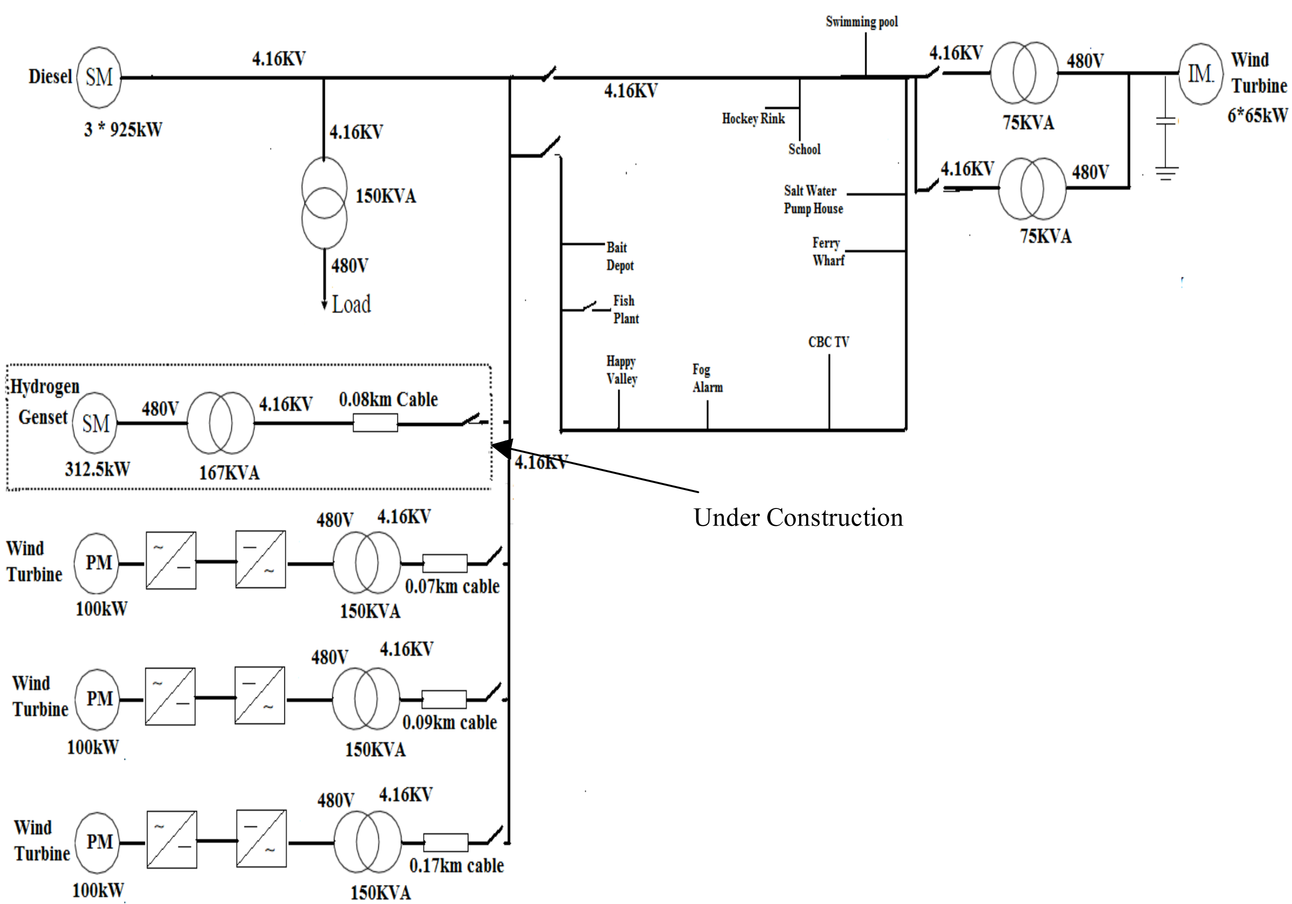

Figure 3: Single line diagram of present Ramea distribution system

The start-up of the 65kW 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. Recently three more 100kW wind turbines were installed and a 312.5kW hydrogen fuel system has been added. Figure 3 shows single line diagram of the present power system in Ramea. All wind turbines produce power at 480V and feed that system through transformers at 4.16 kV. Figure 4 shows location of the wind turbines on Ramea island. The distance between the six old wind turbines and three new wind turbines is about 2km. Hydrogen energy storage system is next to the diesel plant.

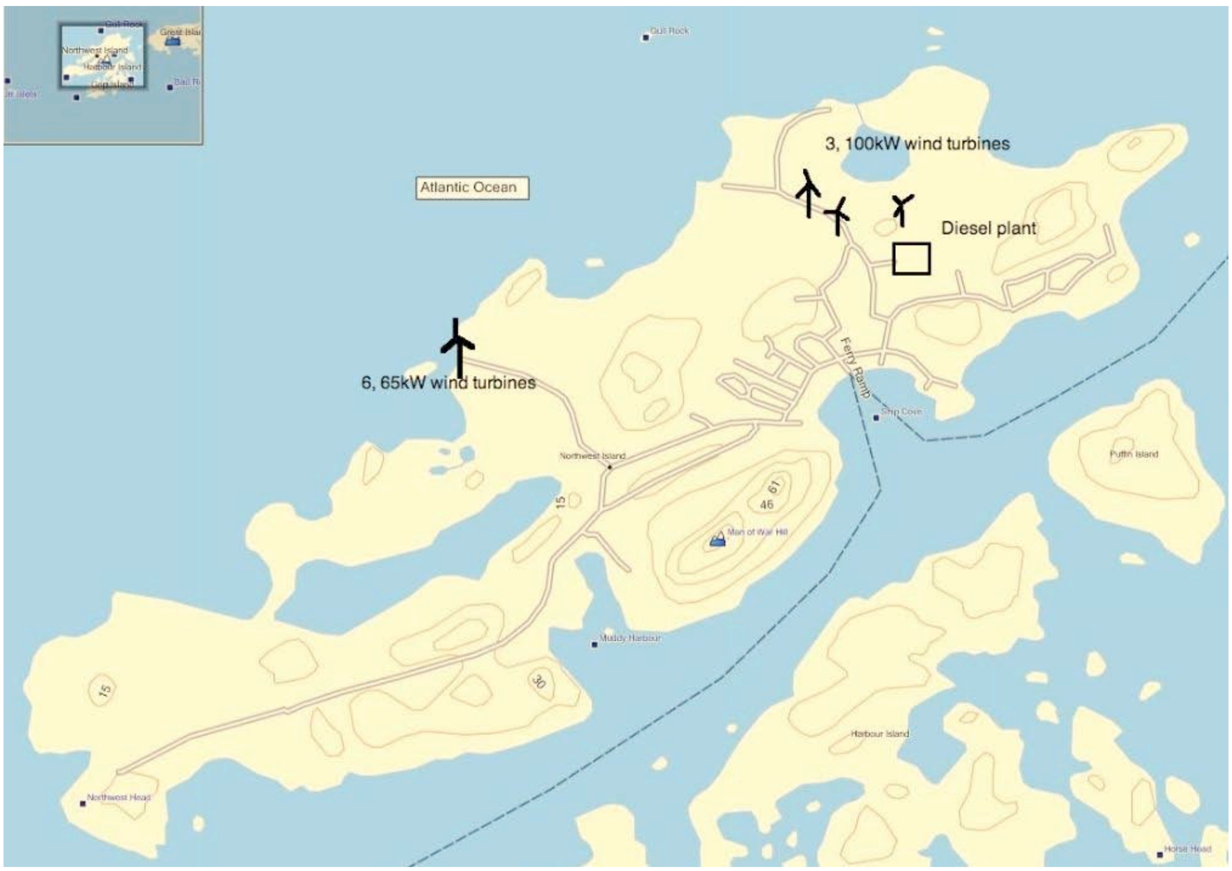

Figure 4: Location of wind turbines and diesel plant in Ramea

Annual average wind speed at 10m height in Ramea is about 6.08m/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 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.

Pump Hydro Storage Systems in the World:

To increase the penetration level of wind energy to the grid the use of wind pumped hydro storage hybrid schemes appear to be the best solution. The first use of pumped storage was in the 1890s in Italy and Switzerland. In 2000 the United States had 19.5 GW of pumped storage generating capacity, accounting for about 2.5% of base load generating capacity. In 2007 the EU had 38.3 GW net capacity of pumped storage out of a total of 140GW of hydropower and representing 5% of total net electrical capacity in EU. For small islands with low installed power the pumped-storage method seems to be the most promising way to utilize the available wind potential at a high penetration level [3]. Theodoropoulos P., Zervos A., Betzios G. [4] propose a hybrid system in Ikaria island near Greece. The electrical supply to most islands in the Aegean Sea is carried out by self-governing diesel power stations. Due to the high load fluctuations internal combustion engines usually work with low efficiency. In order to increase maximum penetration level of renewable energy system and especially of wind energy they redesigned the system from scratch so that wind energy will be the main energy source for the island community and the conventional diesel units will be in the only additional and backup role. The aim of their study was to find the optimum size of each subsystem: i) the capacity of the installed WP, ii) the capacity of the pump-station and iii) the capacity of the reservoirs. Programming and simulation code writing was done in Matlab environment for sizing the hybrid system. After the optimum sizing they found that the hybrid system should compose of: i) Wind Energy Subsystem with total capacity of 5400kW with the existing capacity of 385kW, ii) Mid term storage system with nominal power of 1600kW and iii) Conventional power station with capacity of 6900kW. After simulation they found that the suitable reservoir size is 60000m^3. The pumping unit should be composed of ten 160kW pumps. The simulation results are presented and the optimization procedure is analyzed in [4]. At the end of their study they found that the Hybrid System of Ikaria would be a highly profitable investment.

Katsaprakakis A. D., Christakis G. D., Zervos A., Papantonis D., Voutsinas S. [5] investigated the introduction of pumped storage systems (PSS) in isolated communities of Crete and Rhodes with high thermoelectric production and wind energy. The existing power production system in Crete consists of three thermal power plants with the installed capacity of 677.8MW. In 2004, a 75MW wind park was installed and connected to the Crete power production system. The total thermoelectric installed power in Rhodes was 192MW at the end of 2004. They came to a conclusion that the PSS introduction in isolated power production systems with high thermoelectric production and wind energy is not always economically feasible. The feasibility of the project depends mainly on the particular energy production system. Power production systems with high-energy production, expensive diesel oil with high annual consumption seem to be appropriate for introduction of a pumped storage system.

Bueno C., Carta J.A. [6] propose a wind powered pumped hydro storage system installation on Gran Canaria island (Canarian Archipelago). The results obtained from the application of an optimum-sized economic model of such a system indicate that penetration of renewable sourced energy can be increased by 1.93% at a competitive cost for the unit energy supplied. The total thermal electrical power installed in Gran Canaria on 31

December 2002 was 715.36 MW. Total electricity production from the power stations during 2002 was 2,725,570.55 MWh, with a fossil fuel consumption of 681,175 metric tonnes. Wind sourced power connected to the island grid at the end of 2002 was 74,535 kW, entailing 10.42% of conventional power, with total electricity production in 2002 of 128,588,336 kWh; this means an overall annual penetration of 4.72% of renewable sourced energy fed into the grid. For the proposed system to operate correctly they propose a control algorithm which will make a balance between the total electrical power P_{total} fed into the grid by the three types of power subsystems (diesel power system, pumped hydro storage system, and wind farm) involved and the total demand D_{total} required by the various loads. The iterative method was considered for finding out the optimum combination for their proposed hybrid system. In their result they found that the renewable system which provides the minimum cost of the unit energy supplied (0.084 euros/kWh) consists of 24 WT with a rated output of 850 kW, 89 pumps with a rated output of 200 kW and six hydraulic turbines with a rated output of 10 MW. These results are obtained on the hypothesis that two of the largest existing reservoirs on the island (with a difference in height between the two of 281 m and a capacity of some 5,000,000 m^3 in each) are employed as storage deposits.

Anagnostopoulos J. S., Papantonis D. E. [7] presents a numerical study of the optimum sizing and design of a pumping station unit in a hybrid wind-hydro plant. The aim of their research is to reduce the amount of wind generated energy that cannot be transformed to hydraulic energy due to power operation limits of the pumps and the resulting step-wise operation of the pumping station. A number of wind generators of equal size (600 kW each) are installed in the wind farm, whereas the pumping station contains a number of multistage pumps in parallel operation. The maximum feasible capacity of the upper and the lower reservoir for the specific site considered is about 1×10^6 m^3 with the hydro turbine capacity of 15MW. They considered that the electricity production from the hydro storage system will be for a constant time period every day (usually during the peak demand hours), taken here was equal to 6 hour. Their proposed algorithm refers to characteristic operation curves of commercial pumps, turbines and motors, and performs a detailed calculation of the various hydraulic or electro-mechanical losses. Their evaluation algorithm also performed a detailed economic analysis of the entire plant, using empirical cost-estimation relations for all of its components, including the design and construction costs. The three different pumping station configurations are examined in their research. General, stochastic optimization software based on Evolutionary Algorithms was implemented in their research to find the best solution in a fast and efficient way. They found that the pumping station equipped with a variable-speed pump is the most advantageous configuration, and it can substantially increase the amount of the wind power energy that is transformed and stored as hydraulic energy.

Dimitris Al. Katsaprakakis, Pr. Dimitris G. Christakis, [8] propose a power production system for the island of Astypalaia. Their proposed system aimed at the wind energy penetration maximisation and the imported fossil fuels minimisation, consumed in the electricity production. The proposed system consists of wind parks, a pumped storage system (PSS) and thermoelectric machines. Their whole project was evaluated mainly from an investment point of view. The investment includes only the wind parks, the PSS and the relevant infrastructure (roads construction, utility network, etc). If P_w(Wind power) > P_d(Power demand), the power demand is covered totally by the wind parks. The PSS pumps are provided with the wind power surplus $P_p=P_w-P_d$, in order to be stored in the PSS upper reservoir. If $P_w < P_d$, the produced wind power is totally offered to the power demand cover. At the same time, a power supplement $P_h = P_d - P_w$, produced by the PSS hydro turbines, replaces the wind power shortage. The wind turbine capacity was considered about 850kW for this island. The upper reservoir capacity form the pumped hydro system is selected in terms of the hydro turbines autonomy operation days number and the available head height for the system. They used iterative calculation for several combinations regarding the upper reservoir capacity and the wind parks, hydro turbines and pumps nominal powers for getting the optimum combination for the hybrid system in Astypalaia. They found that the hybrid system should consist of 150000 m^3 reservoir capacity, 4.25MW wind farm, 2MW hydro turbine, 2.5MW pumping system.

Above literature review indicates the research and use of pump hydro storage system in a number of remote wind diesel facilities. Pump hydro energy storage system is not a new idea and it is a well established technology. It is one of the most reliable and well tested methods of large scale energy storage. Power industries continue to add pumped hydro storage system in isolated grids for increasing the wind energy penetration level to the existing power grid systems. Instead of using a high tech low overall efficiency hydrogen based energy storage system we propose a pump hydro energy storage system for Ramea, Newfoundland. The following sections describe the details of our research work on Wind-Diesel-Pumped Hydro storage system for Ramea, Newfoundland.

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 site and system data. An analysis of current configuration of Ramea hybrid system was done using HOMER. Purpose of this analysis is to determine expected performance of the system. All system parameters and costs were obtained from NL Hydro. 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. Annual wind speed data for Ramea is shown in Figure 5. The data used in this research was collected from NL Hydro and Environment Canada [9]. From the wind speed data it is found that the annual average wind speed is about 6.08m/s at 10m height which indicates that this area has one of the highest wind resource regions in Canada. Maximum wind speed is 21.6m/s. Winter months are windy as compared to summer months. Average wind speed in December and in January is 9m/s. Community power requirement is also highest during the winter months. It means using wind energy to reduce diesel consumption makes sense. Wind speed probability distribution function is also shown in Figure 5. It indicates that probability of wind speed of 5m/s is 14%. Electrical load profile of Ramea is shown in Figure 6. Daily profile indicates that load varies from 350kW to 610kW every day. Monthly profile indicates higher electrical load during winter months than summer months in a year. Load profile also indicates that for a few days in winter the load may be as high as 1100kW.

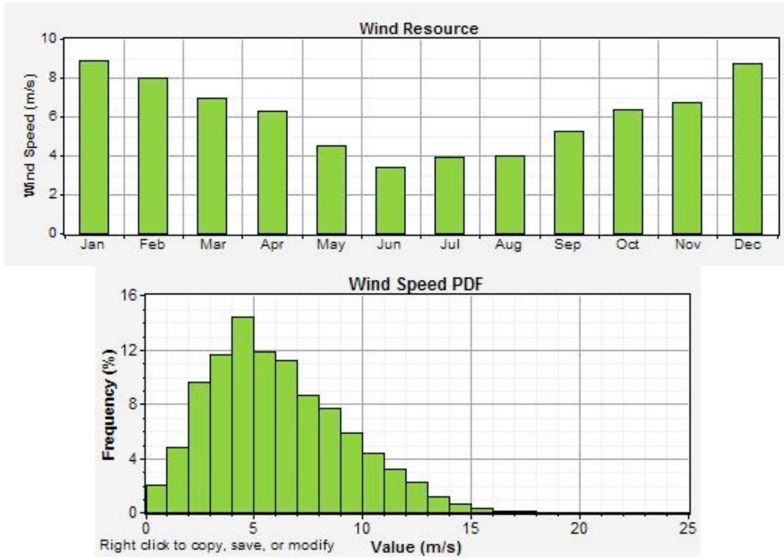

Figure 5: Annual wind speed data of Ramea

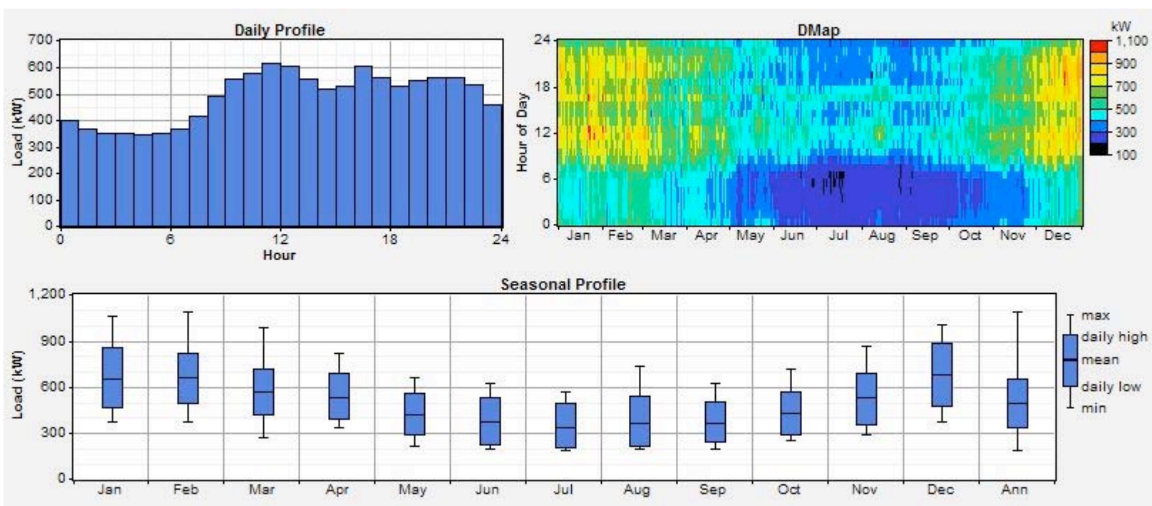

Figure 6: Electrical load profile of Ramea

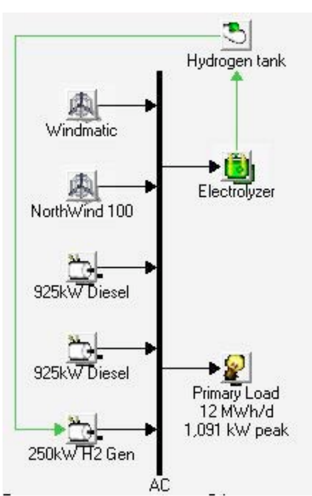

Figure 7: Ramea Hybrid System

Figure 7 shows current Ramea hybrid power system as simulated in Homer. It has only an ac bus. Excess electricity from the wind turbines is converted to hydrogen using an electrolyser. Hydrogen is compressed and stored in three large tanks. Stored hydrogen is used to generate electricity when needed. All system parameter including costs were obtained from NL Hydro. System expected performance was analysed and it is presented in Figure 8. It shows that expected renewable fraction is 37% and cost of electricity would be \$0.248 per unit. One 925kW diesel is always running. Second diesel would be needed only for 12 hours in a year. Hydrogen generator will run only for 702 hours in a year. Expected electrical performance is shown in Figure 9. It shows that the hydrogen generator

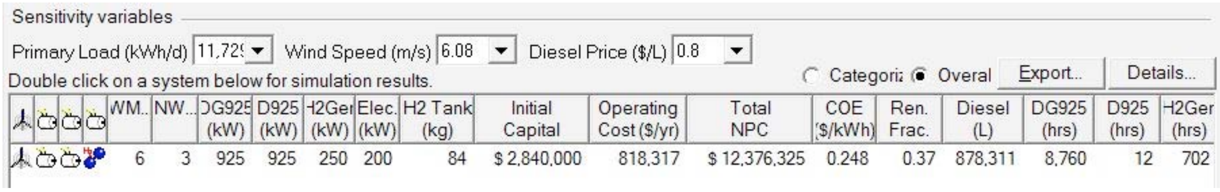

Figure 8: Simulation results of the hybrid system in Ramea

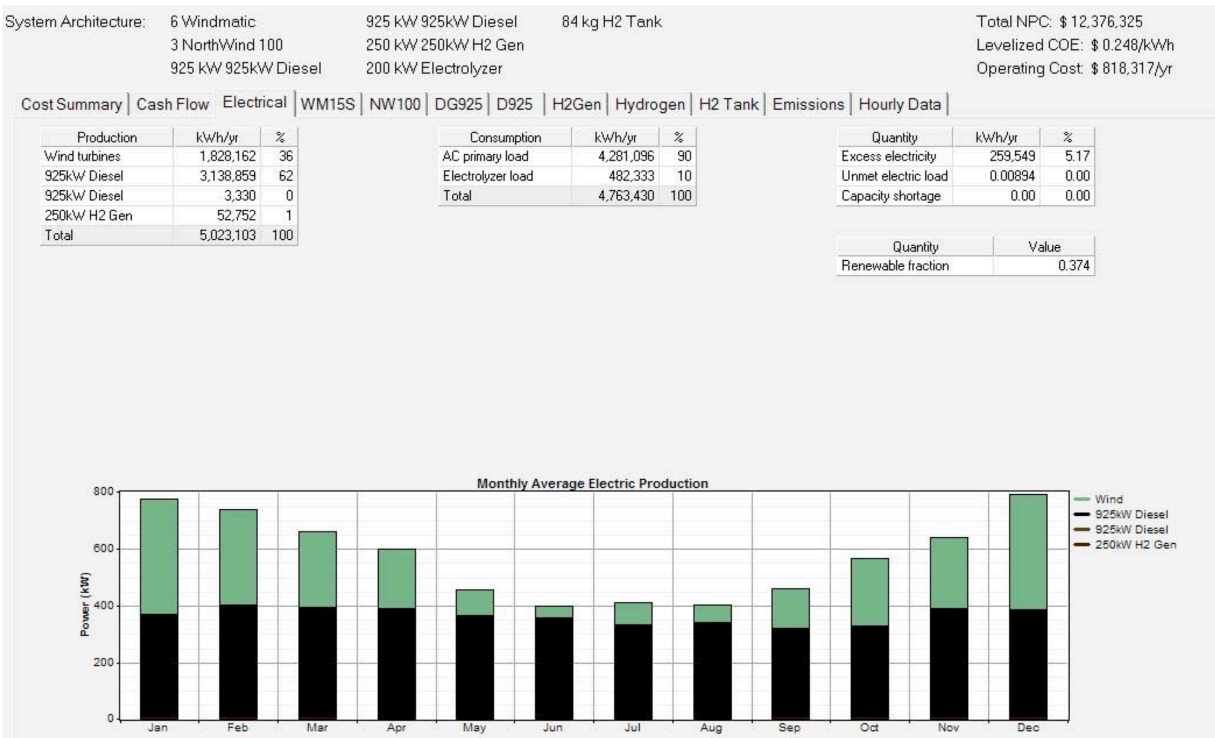

Figure 9: Expected electrical performance of Ramea hybrid system

will contribute only 1% of electricity to the system, while electrolyzer will consume 10% of 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 optimization software HOMER. Hydrogen energy storage system shown in the 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 hours in a year. 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.

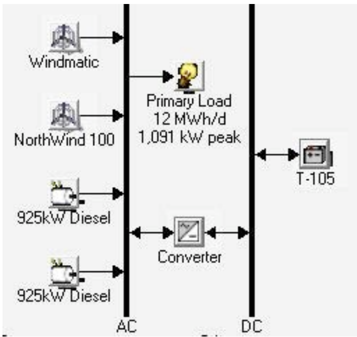

Figure 10: Ramea hybrid system with a battery storage.

In HOMER simulation it is assumed that the interest rate is 7% and the project lifetime is 25years. Simulated hybrid energy system is shown in Figure 10. With a condition of 40% renewable energy fraction, the optimized homer simulation results including sensitivity variables are shown in Figure 11. Renewable energy fraction for all cases is about 37%. From Figure 11, it is clear that yearly diesel consumption reduces with the battery size. The larger the battery size 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 250kW converter between AC and DC bus.

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. Categori: Overal 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 11: HOMER optimized results.

The nominal capacity of each T-105 battery is 1.35kWh. The expected electrical performance of the hybrid power system is shown in Figure 12. 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 11 and it is less than what is shown in Figure 8. Figure 12 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. So during summer most of the electricity demand will be met from the diesel. Figure 12 also shows that the total electrical energy required for that area is 4,281,096 kWh/year and 37% of that will be met by the wind energy including the system peak demand. Figure 13 shows monthly statistics and expected frequency histogram of battery state of charge. On average battery will be 70% charged. (i.e. upper reservoir will be 70% full) 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 few meters above sea level. Head of few meters is not good for a pump hydro installation. The hills in Ramea can be used for such a purpose.

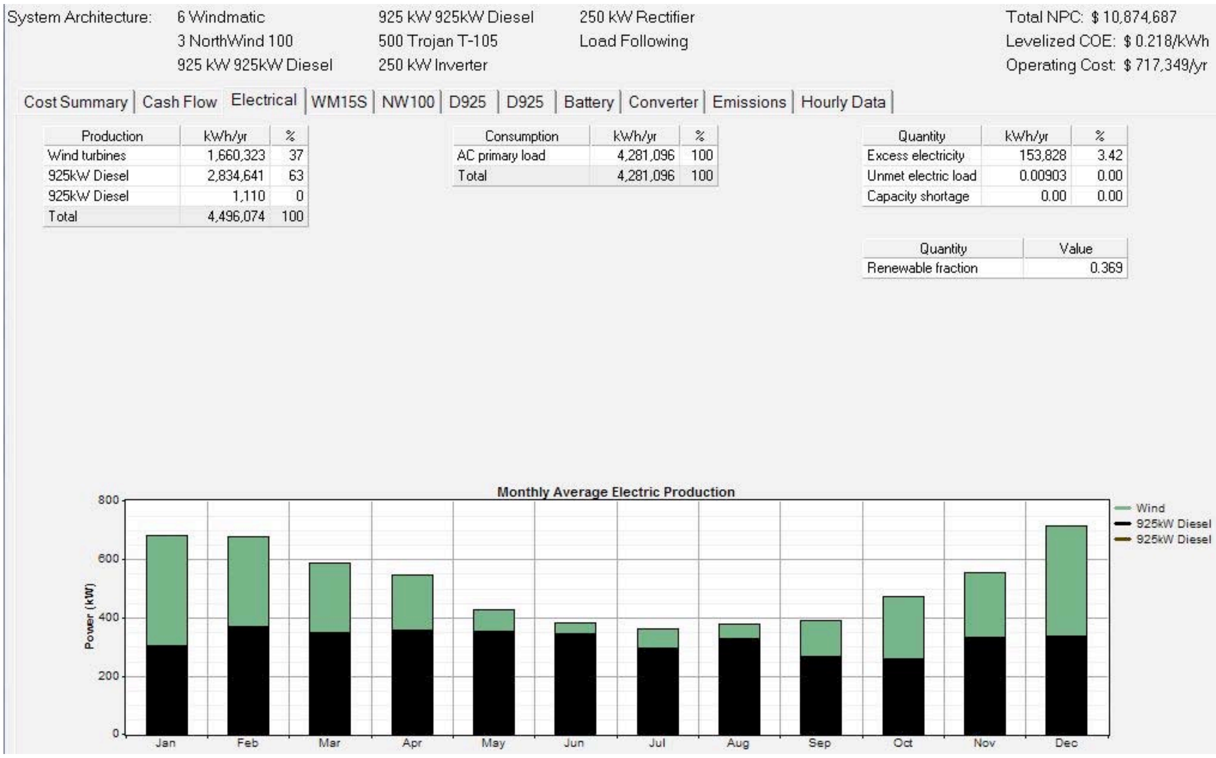

Figure 12: Expected electrical performance of the proposed hybrid power system.

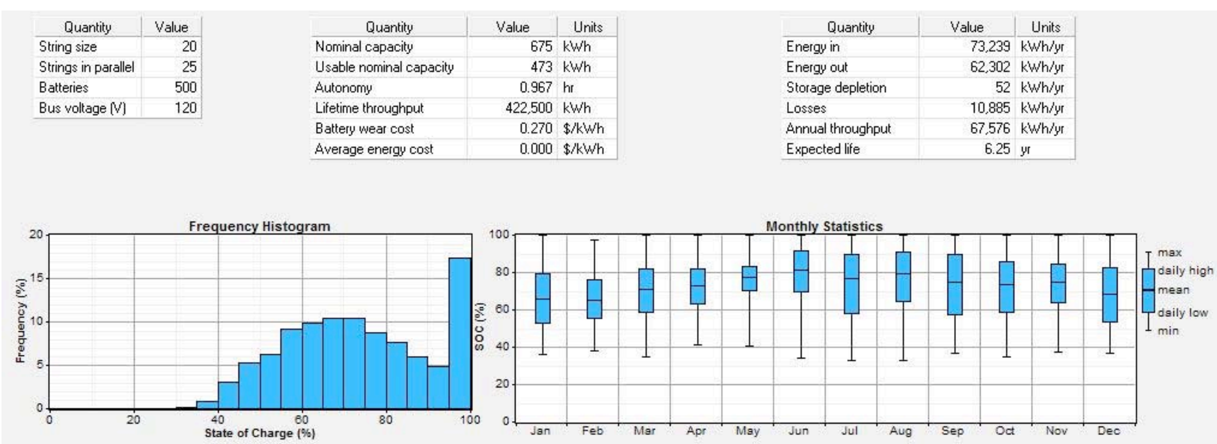

Figure 13: Expected energy in and out of battery storage system.

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 Hill (see Figure 4). It is a potential place where a hydro reservoir can be built at 63m height. Access to this hill is not an issue as there is a telecommunication tower already installed for community's communication on the next hill. The Man of War Hill is one of the highest hills in Ramea and presently nothing exist there. It has significant area on the top and it is very close to the water i.e. required length of penstock would be minimum.

In a hydro power plant, potential energy of the water is first converted to equivalent amount of kinetic energy. The potential energy stored in the upper reservoir should be same as the energy stored in the batteries suggested by HOMER. Figure 12 shows we will need 500, Torjan T-105 batteries (each 1350Whr). So the potential energy stored in the upper reservoir should be.

Potential Energy = mgh, → 1350 × 3600 × 500 = mgh = (volume * desnsity)*g*h

$$\rightarrow V = \frac{1350 \times 3600 \times 500}{9.81 \times h \times 1000}$$

For a head h = 63m, required reservoir size will be V = 3932m^3 (equivalent to 500 batteries). Figure 13 shows the topographical location of Man of War hill in Ramea. From the figure 13 it can be seen that about 2000m^2 area is available to build a hydro storage reservoir.

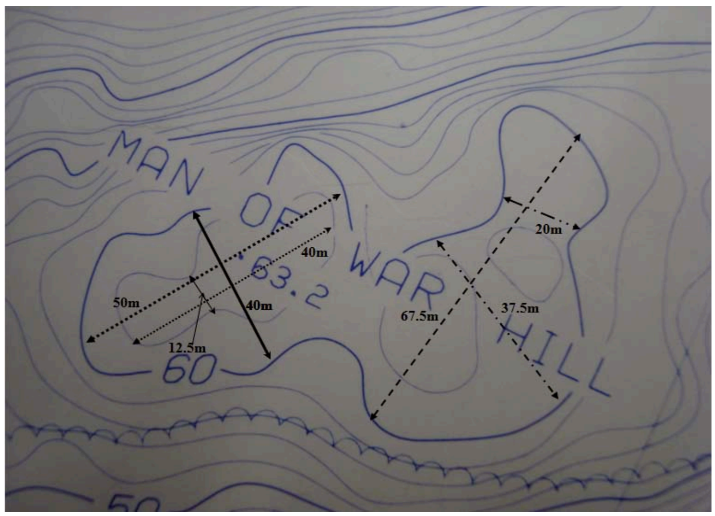

Figure 13: Topographical map of Man of War hill.

So the height of the reservoir will be 2m 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 10. From HOMER time series data it was found that during April maximum power flow from the converter is 147kW. Figure 14 shows expected output of converter in June. It shows that we might be taking power from the reservoir for more than 3 hours.

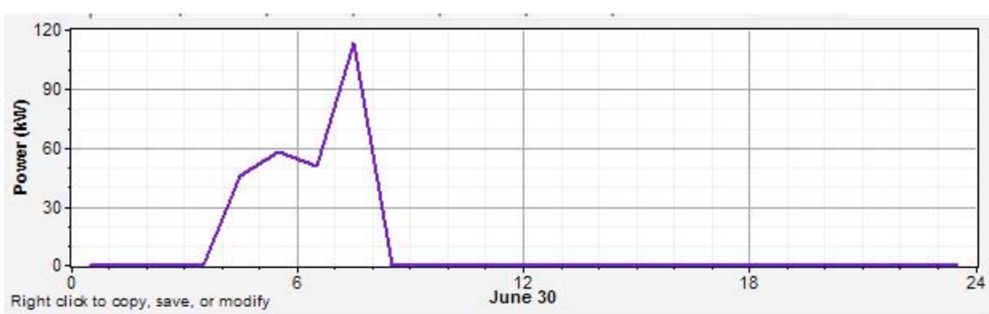

Figure 14: Output of converter in June.

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 147kW $\simeq$ 150kW, the usable flow rate can be calculated using the following equation:

$$P = \eta \times Q \times H \times g$$

Here P = Power output in kW = 150kW, Q = Usable flow rate in m^3/s, H = Gross head in m (63m), g = 9.81 m/s^2 and η = Hydro turbine efficiency = 70%. From above equation we determined flow rate Q = 0.347 m^3/s. The minimum operating time for the hydro turbine will be = 3932 m^3/0.347m^3/s = 11331 s = 3.14 hrs. Figure 15 below shows a possible site for a pump hydro facility. The proposed pumping and generating station could be about 100m from the top reservoir and about 60m from the existing 4.16kV transmission line.

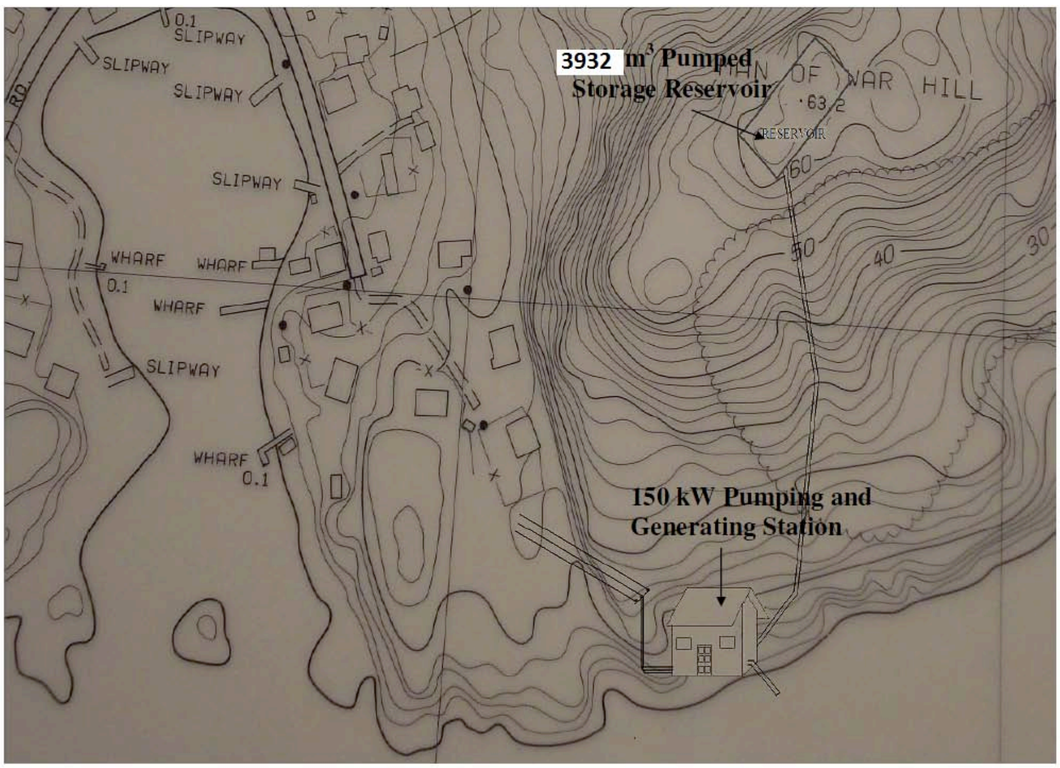

Figure 15: Possible location of pump hydro energy storage system in Ramea

Dynamic simulation of grid connected PHS:

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 utilise 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 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 65kW wind turbines, three 100kW wind turbines, and diesel plant. The stored energy will be used to produce electricity during peak times throughout the day. Hydro turbines can be broadly categorised into either impulse or reaction turbines. Figure 16 shows a guide for selection of hydro turbine. (http://www.microhydropower.net/download/layman2.pdf) For the Ramea site the expected flow rate is 0.347 m^3/s and head is 63m therefore the best selection from the Figure 16 is a pelton or turgo type turbine.

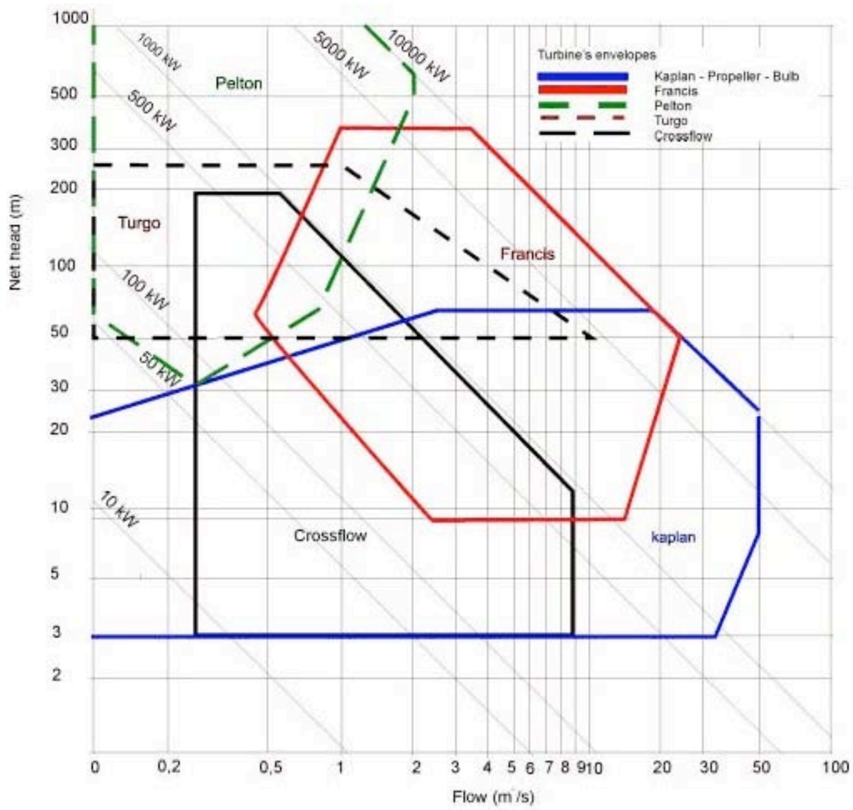

Figure 16: Turbine Selection based on head and discharge

References [10, 11, 12] 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 was done to determine expected power quality. Simulation was also done to find out if an addition of a 150kW pump hydro unit will greatly impact the stability of the system. Figure 17 shows diesel-wind-hydro hybrid power system in Ramea simulated in SIMULINK. From Figure 8 and 11 it can be seen that only one diesel generator is running at a time. That why dynamic simulations were done considering only one diesel in the system. In Figure 17, 390kW and 300kW block representing all 65kW and all 100kW wind turbines in Ramea respectively. Here the pump is considered as a 150kW centrifugal pump with induction machine and hydro turbine is considered as 150kW unit with a synchronous machine coupled to the system bus. Community load is considered as a constant load and system was simulated for 24s. It took a quad core processor based computer more than 3 hours to complete one 24s simulations. The system was studied for a varying wind speed.

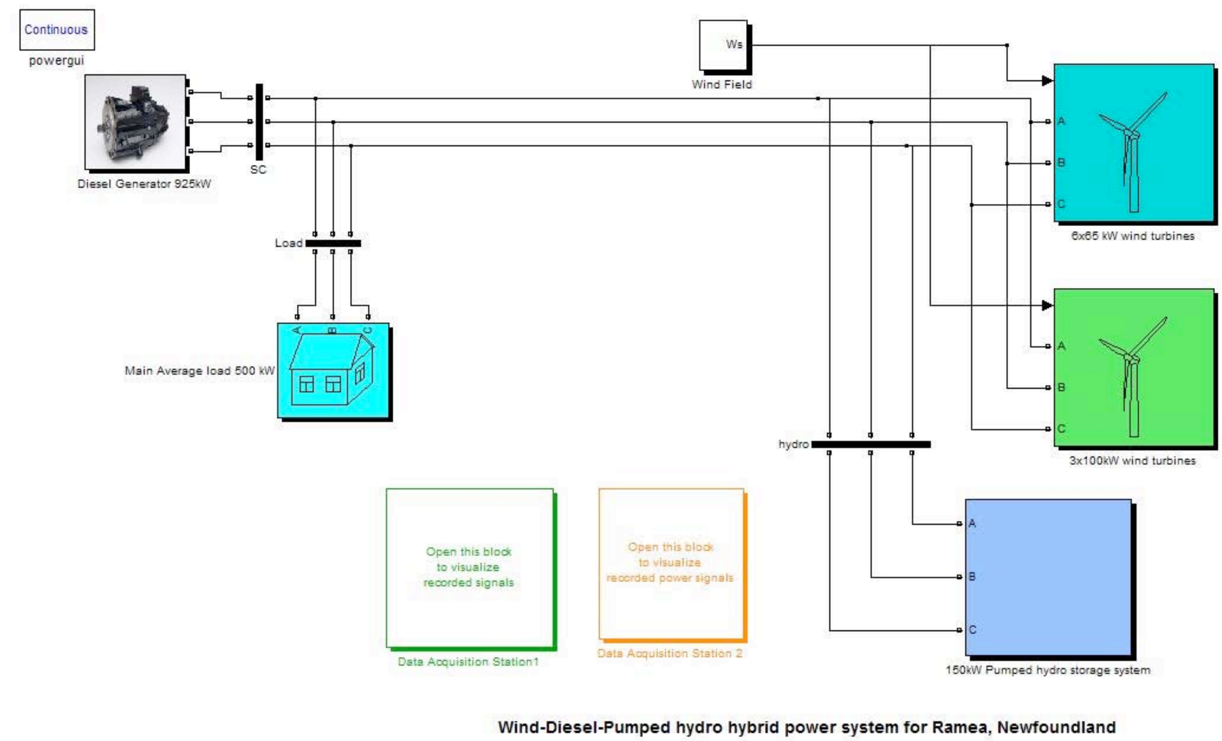

Figure 17: Diesel-wind-hydro hybrid power system in Ramea

In order to determine the system voltage and frequency variations the following equations were used to generate a wind field [13].

$$V_w = V_t + V_a$$

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

Here V_w is the wind speed, which is composed of average wind speed component (V_a) and turbulence component (V_t). The average wind speed value is chosen as 8.02m/s. The $m_w(t)$ is random white noise which is used to generate the turbulence component within the wind field. The z is the turbine height and V_0 is maiden wind speed.

With the wind speed characteristics applied to the simulation, assuming a constant load of 500kW at Ramea. During our simulation it is considered that the pumping motor will operate for the first five seconds and than it will be switched off. At 11^{th} second hydro turbine will start and it will operate for five seconds and than it will switch off. It is understood that such a 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. (One minute simulation took more than 3 days of computer time. The computer often hang up or simulation code crashed before simulation was done for one minute) Switching after 5 seconds well represents the transient in the system. Simulation for 24 seconds gave a good idea of expected transient in the system.

Figure 18 shows some results of system dynamic simulations. Figure 19 shows power variations in the system. From Figure 18 a voltage dip and a current surge can be seen that for the first five second when induction motor is running the pump to store water in the upper reservoir. Diesel engine tried to maintain the power balance by running faster and system frequency increased to 61Hz. At t=5s pump was switched off and the system came back to its original state within few seconds. At 11th second hydro turbine is switched on for 5 seconds. This leads to another transient in the system. Figure 18 also shows expected variation in the system voltage, frequency and current during this transient. It can also be noted in figure 18 that small variation in the wind speed is not leading to any significant transient in the system. Figure 19 shows expected power variation in the system. It can be noted in Figure 18 and 19 that simulation was not perfectly converging between t= 11s and t=16s. Significant time was spent to resolve this issue but this remained unresolved. Various methods of integration were tried but all led to similar results.

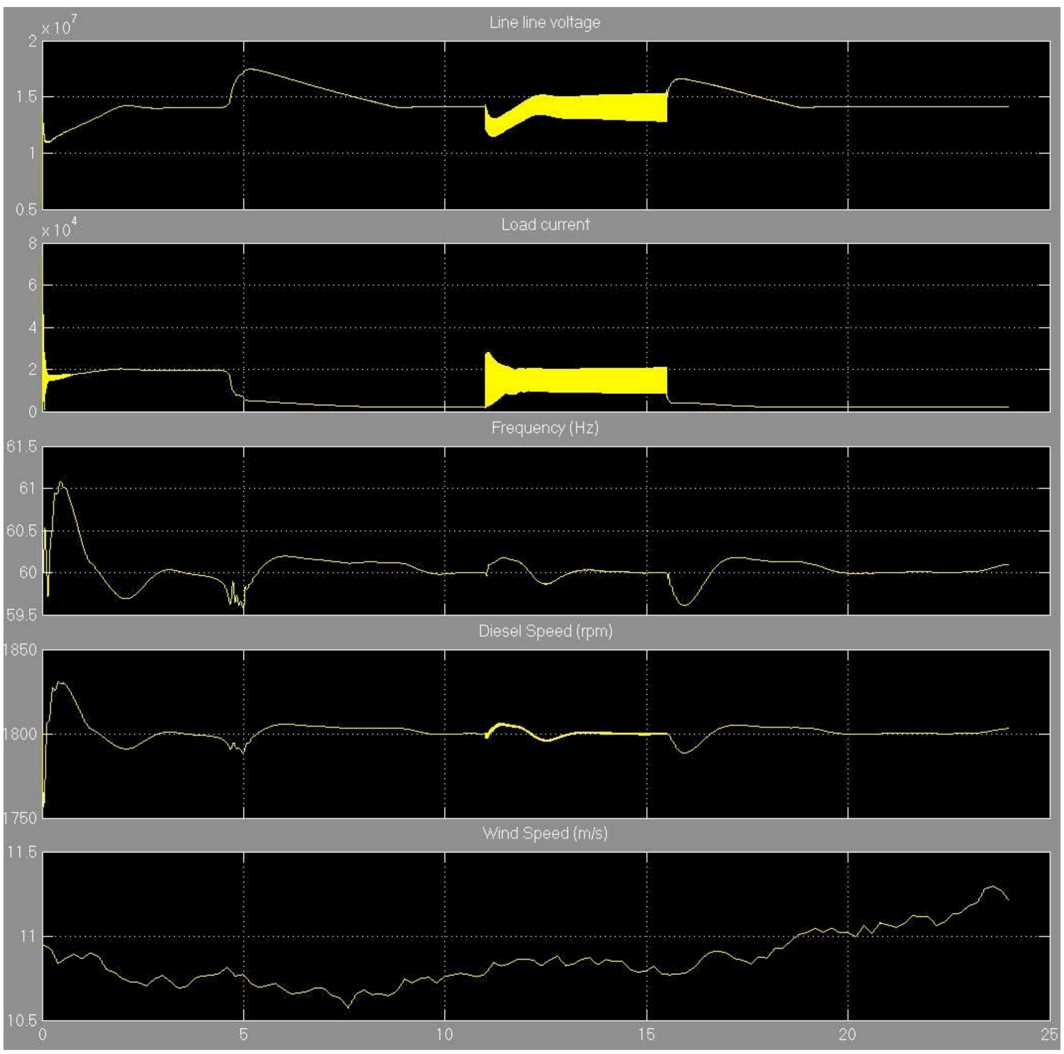

Figure 18: Expected transients in the Ramea hybrid power system

Figure 19 shows 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 steady state voltage and frequency change in the connected grid system. The voltage and frequency variation at load end is given in Figure 18. From Figure 18 it can be seen that the expected voltage variation and the frequency variation 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 end in remote locations is required to be within ±10% [14]. Some voltage variation can be counteracted by adjusting the power factor of the wind turbines [15]. Therefore, the expected voltage and frequency variations in the proposed Ramea wind diesel pump hydro generation system are within current power quality standard.

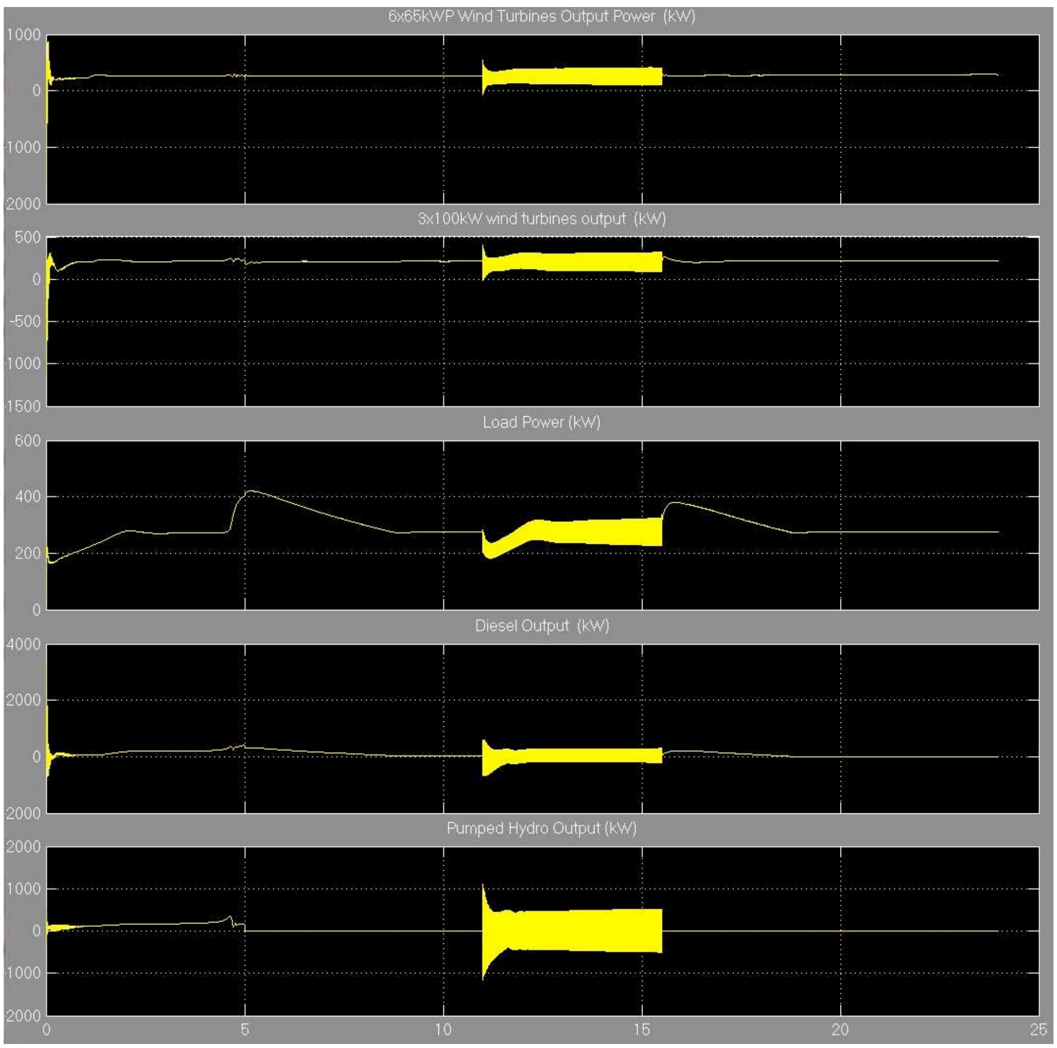

Figure 19: Expected power changes in a transient condition in the Ramea Hybrid power system

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 4000m^3 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 63m and can use sea water. A 150kW 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 37% renewable energy fraction and result in an acceptable electrical transients in the system. By 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 [16] 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.

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