Autonomous Renewable Electricity Supply for Residential Use: Case Study of an Off-grid House in Brooklyn, Wellington

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New Zealand is one of the countries with the best renewable energy resources in the world. Apart from its ample hydro resources, it has an excellent wind potential, which the Global Wind Energy Council refers to as a fantastic energy source, and there are other resources such as geothermal, solar, biomass, wave etc. that are also abundant in the country. The country currently generates about 75% of its electricity from renewable sources; increasing this proportion to 90% by 2025 has also been an agendum of the present government. This ambition raises a question in the minds of the people as to which of the energy resources are likely to produce the 15% additional energy. In recent times, some homes have considered the option of incorporating small-scale generation systems to their households, such as roof-mounted solar PV and micro-wind systems. The expectation of the users being that any excess energy produced by these systems is sold to the grid, thereby, facilitating reduction in their electricity bills, while energy is being purchased from the grid when the output of the systems cannot satisfy the users' consumption. This process however depends on the electricity retailer and the buyback price. The fact that the current buyback prices are less than the grid purchase prices is one of the factors affecting the widespread use of such systems within the residential sector, in the country. On the contrary, such on-site generation systems have been identified as a better choice for off-grid households, where it is very expensive to get access to the power grid. In this case, an energy storage system is required to balance the variability of the renewable resource, and also to store excess energy. In this paper, we discuss a stand-alone hybrid electricity system (HES) for off-grid residential use, based on wind, solar, and petrol-generator with a suitable battery bank, using a house in Brooklyn as a case study. The HES is developed to adequately manage an average daily demand of about 10kWh for lighting, TVs, refrigerators, DVD players, computers, phone chargers, etc., excluding cooking, hot water and heating appliances. We present the technical considerations and the environmental impacts of the system, and also conduct a Life Cycle Cost Analysis (LCCA) to compare the economics of the HES with only petrol-generator system, thus, investigating the cost benefits. The problems encountered during the implementation of the energy system are also enunciated in the paper.

1. Introduction

New Zealand is one of the countries with the best renewable energy resources in the worldwide [1, 2]. Apart from its ample hydro resources, it has excellent wind energy resources, which have been referred to as a "spectacular" energy potential by the Global Wind Energy Council (GWEC) [2], there are other renewable resources such as geothermal, solar, biomass, wave, and tidal that are also huge in the country. The country currently produces about 75% [2-6] of its electricity from renewable sources, and its present government has also set a target of achieving 90% renewable electricity generation by 2025 [3]. Though renewable energy resources are believed to be instrumental to the realization of this target within the next decade, a question is however raised in the minds of the people as to which of the available resources are likely to supply the 15% additional energy. In recent times, some homes have considered the use of small generation systems, such as roof-mounted solar PV and micro-wind systems. The reduction in the prices of PV modules is one of the factors which have contributed to increased interests in PV systems [7], while the possibility of micro-wind energy systems is also being explored for harnessing the abundant wind resource in New Zealand [8]. For grid-connected households, the excess generation by the systems is usually exported to the grid, with the expectation that the electricity bills will be reduced, while energy is being purchased from the grid whenever the output of the systems cannot satisfy the users' consumption. This process however depends on the electricity retailer and the buyback price [9]; furthermore, the current buyback prices, which are less than the grid purchase prices, is one of the factors affecting the widespread use of such systems within the residential sector, in the country. On the other hand, such systems have been identified as a better choice for off-grid households, where it is very expensive to get access to the power grid. They are also apt for isolated farms, schools, small community, community centres etc. They are clean, environmentally-compatible and sustainable [10-14], but in any case, they need to be properly designed to satisfy the load conditions.

This paper presents a system design and analyses of a small hybrid electricity system (HES) that is being implemented in Brooklyn, Wellington, New Zealand, for grid-independent household applications. The HES consist of wind, solar and a suitable battery bank, including a generator used as a back-up. The system supports an average daily demand of about 10kWh for lighting, TVs, refrigerators, DVD players, computers, phone chargers, etc. in the house, excluding cooking, hot water and heating appliances. While cooking is achieved by using gas/wood, water and space heating are accomplished by utilizing gas; ironing of cloths is also achieved on a very windy day, when there is excess generation or by using the generator. Apart from the technical considerations, we conduct a Life Cycle Cost Analysis (LCCA) to investigate the cost benefits of the HES, in comparison with only generator. The environmental benefits are evaluated in terms of fossil fuel saved. The implementation challenges of the system are also articulated in the paper.

The remaining part of the paper is organized as follows: section 2 concentrates on the wind and solar resource in Brooklyn, section 3 focuses on the methodology; section 4 presents the results and discussion; section 5 discusses the implementation challenges, while the paper is concluded in section 6.

2. Wind and Solar Resources of the Location

The site is located on a hill at Brooklyn and it experiences an undisturbed wind and appreciable solar energy resources. Based on this, the wind/PV option in chosen, rather than depending on a single-source configuration only – e.g. wind or solar, which will demand higher battery size [15]. Figs. 1, 2 and 3 show the hourly wind and solar resources for the selected days, while Figs. 4, 5 and 6 illustrate the average - air temperature, wind speed and peak sun hours (PSH), respectively, for the year 2012 [16]. These days are selected at random to showcase the intermittent nature of the energy resources. It can be observed from Figs. 1, 2, 3, 5 and 6 that though wind and solar are both variable sources, they possess different characteristics. Therefore, their combination is expected to offer a complementary advantage. In addition, the air temperature and irradiance values during the summer are relatively higher than the values obtained during the winter period, as presented in Figs. 2, 3 and 4. The highest and the lowest solar irradiation have been obtained in January and June, respectively, with the values of 6.53kWh/m^2 and 1.42kWh/m^2, correspondingly. Similarly, the highest and the lowest average wind speeds of 6.2m/s and 3.3m/s were recorded for October and August, respectively. It is also glaring from Fig. 6 that the winter months experience lower irradiance values compared to the summer months.

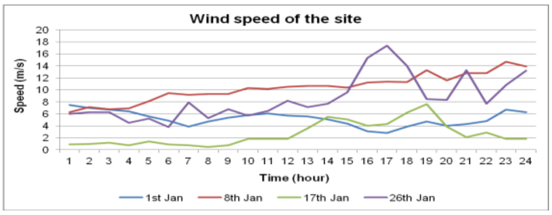

Fig. 1. Hourly wind speed

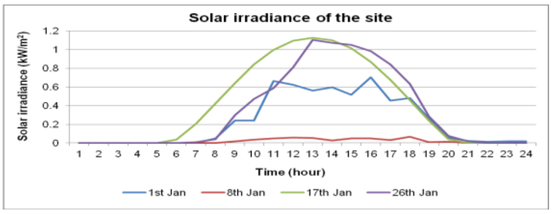

Fig. 2. Hourly solar irradiance (summer)

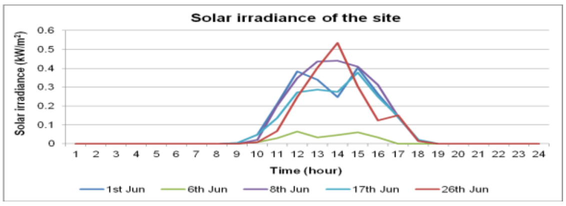

Fig. 3. Hourly solar irradiance (winter)

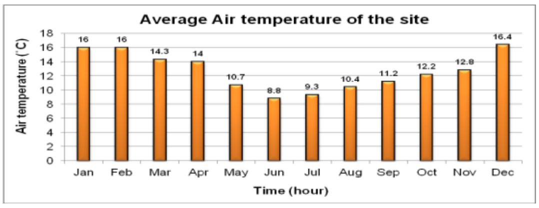

Fig. 4. Average ambient temperature

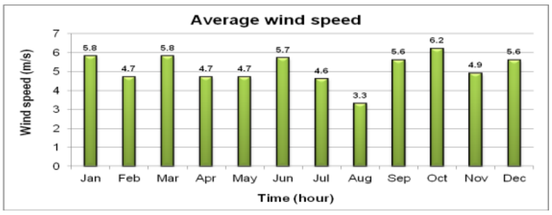

Fig. 5. Average wind speed

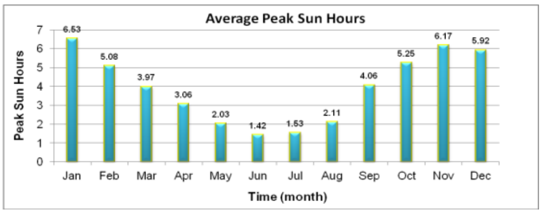

Fig. 6. Average PSH

2.1 Demand model

The load profile of the house is shown in Fig. 7, with a peak daily energy requirement of about 10kWh, translating to a yearly demand of around 3,650kWh, from energy efficient appliances, most of which have an “ENERGY STAR” label. Because water heating, space heating and cooking are being achieved by other energy sources of energy in the household, there is little or no difference between the electricity consumption in the house during different seasons – winter and summer. The peak demand is in the evening, which is about 1kW, as shown in Fig. 7.

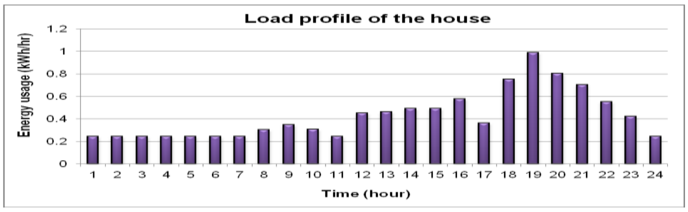

Fig. 7. Load profile

3. Methodology

3.1 HES model

To develop the HES, it is necessary to design the main components – wind generator, PV array, battery and generator, and then integrate them to supply the pre-determined load. Fig. 8 shows the block diagram of the HES.

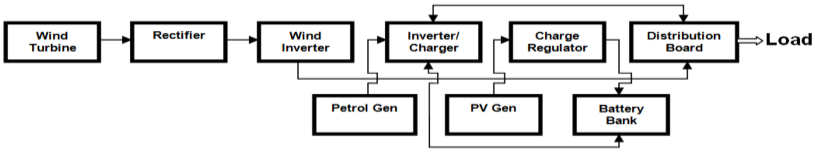

Fig. 8. Wind/PV/Battery/Gen

3.1.1 Wind turbine

Wind turbine systems are usually rated by the amount of electrical power they can safely deliver at a certain wind speed [17]. This power could be estimated by eq. (1) [17 - 19]:

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

where ρ, C_p , A and V are air density (kg/m^3), maximum power coefficient, the swept area by the blades and the wind speed, respectively; $A = \pi R^2$, where R is the radius of the rotor. The power coefficient is the "ratio of the power extracted by a wind turbine to the power available in the wind" and it has typical values between 0.25 and 0.45, with a maximum "theoretical" value of 0.593 - usually referred to the Bertz limit. From eq. (1), a small increase of wind speed could potentially yield a large increase in power, P. The size of the turbine rotor also affects wind turbine performance, as it dictates the swept area and the wind speed. Wind speeds also increase with height, thus, affecting the energy delivered by turbines. The wind speed at a particular hub height is estimated by the power law given by eq. (2) [20, 21]:

$$V = V^{rf} \left(\frac{h}{h^{rf}} \right)^{\alpha} \tag{2}$$

where V is the wind speed (m/s) at the hub height, h(m); V^{rf} is the wind speed (m/s) at a "reference height", h^{rf} (m), while α represents the coefficient of ground surface friction; α ranges from <0.1 for flat terrain, water or ice to >0.25 for largely forested terrains [1]. A value of $\alpha = 0.2$ is used in this study because of a few trees around [22]. The wind turbine presented in this paper employs a direct-drive permanent magnet generator, and so there is no gear box in its arrangement, which facilitates low noise and enhanced system reliability [23].

3.1.2 PV system

The power output of a PV module/array is given by eq. (3) [7, 15, 20, 21, 24-26]:

$$P^{pv} = \eta A_{array} P_r G_{inc} \tag{3}$$

where P_r, A_{array} and G_{inc} stand for rated power (W), area of PV array (m^2) and the irradiance received by the PV (W/m^2); η is the efficiency of the PV and it is represented by eq. (4):

$$\eta = \eta^{stc} \left[1 + \lambda (T_c - T_{c,stc}) \right] \tag{4}$$

where η^{stc} is the module efficiency at STC; λ is the PV temperature coefficient of power in (%/˚C); T_c and $T_{c,stc}$ are the actual cell temperature (˚C) and the cell temperature at STC, respectively. The actual cell temperature is given by eq. (5):

$$T_c = T_{amb} + \left(\frac{NOCT - 20^\circ}{800} \right) G_{inc} \tag{5}$$

where T_{amb} and $NOCT$ are the ambient temperature (˚C) and the nominal operating cell temperature, respectively. The typical values for η^{stc}, λ and $NOCT$ are obtained from the PV manufacturer datasheet.

3.1.3 Battery storage system

A suitably designed battery energy storage is crucial to the good working of a stand-alone system because of the overriding need to balance the intermittent energy supply by the renewable energy resources, to store excess energy generation and then provide it for the user when needed [6]. The size of the battery, B_{cap} is given by eq. (6) [20, 21, 23]:

$$B_{cap} = \frac{E_{load} . A_d}{V^b . MDOD . \eta_b} \tag{6}$$

where E_{load}, A_d, V^b, $MDOD$ and η_b are peak daily demand, days of autonomy, the battery voltage, maximum depth of discharge and battery efficiency, respectively. In this paper, the values of V^b, $MDOD$ and η_b are 24V, 0.8 and 0.8, respectively.

3.1.4 Generator

The generator is selected based on the assumption that the appliances to be operated include pressing iron, printer/photocopier etc. The average load of the profile shown in Fig. 7 is about 430W, and with the addition of the pressing iron, printer/photocopier, hair clipper and microwave oven, a 5.5kVA HONDA generator is selected.

3.2 Economic analysis

The life cycle cost (*LCC*) of the Wind/PV/battery system is defined by eq. (7), where C_{ic} represents the initial capital; C_{om} and C_r stand for the present value of operation and maintenance (O and M) and replacement costs, respectively [27]:

$$LCC = C_{ic} + C_{om} + C_r \tag{7}$$

The initial cost, C_{ic} includes the cost of wind turbine, solar modules, batteries, rectifier, charge regulator, inverter and the other balance of system (BOS) such as cables, distribution board etc., and the installation cost. The present value of C_{om} and C_r, and the annual life cycle cost (*ALCC*) are calculated by employing the present value coefficient (*PVC*) and the capital recovery factor (*CRF*), which are presented in eq. (8) and (9) respectively, where the inflation rate (%), interest rate (%), project lifetime (years), and expected life of components (years) are represented by r^i, i, P_{lf} and n, respectively. In this paper, r^i, i and P_{lf} are assumed as 6%, 5%, 25 years. The installation cost of the wind turbine is about 36% of its initial cost, while the installation cost of the PV system is about 50% of its initial cost. The expected life of the wind turbine system, PV modules, charge controller and inverter is 25 years, while the batteries have a life span of 15 years. The total C_{om}, C_r and the fuel cost for the generator are also analysed by calculating their present value. The cost of energy (*COE*) over the project lifetime is given by eq. (10), where HES_{yearly} is the annual energy produced by the system.

$$PVC = [(1+i).(1+r^i)^{-1}]^n \tag{8}$$

$$CRF = r(1+r)^{P_{lf}}.((1+r)^{P_{lf}} - 1)^{-1} \tag{9}$$

$$COE = \frac{ALCC}{HES_{yearly}} \tag{10}$$

The fuel consumption rate, F_{gen} (litre/hr) of the generator for the load profile is evaluated by eq. (11)[11, 28]:

$$F_{gen} = \alpha P_\alpha + \beta P_\beta \tag{11}$$

where P_α and P_β represent the operating output power (kW) and the rated generator power (kW) respectively. Also, the fuel curve slope and the fuel curve intercept coefficient are represented by α and β, respectively. These two parameters are given as 0.246litre/kWh and 0.08415litre/kWh, respectively. Three scenarios are considered for the LCCA such as:

- scenario 1 – generator only
- scenario 2 – Wind/PV/Battery only
- scenario 3 – Wind/PV/Battery plus generator

3.3. Environmental analysis

In this paper, the environmental benefit is evaluated in terms of the amount of fossil fuel saved by the application of renewable energy technologies. The maximum amount of fuel saved, F_{saved} (max) in litres, is given by eq. (12):

$$F_{saved}(\max) = F_{scenario1} - F_{scenario2} \tag{12}$$

where $F_{scenario1}$ represents the amount of fuel consumed by scenario 1, $F_{scenario2}$ stands for the amount of fuel consumed by scenario 2. Also, the minimum amount of fuel consumed, F_{saved} (min) is given by eq. (13):

$$F_{saved}(\min) = F_{scenario1} - F_{scenario3} \tag{13}$$

where $F_{scenario3}$ is the quantity of fuel saved by scenario 3.

4. Results and discussion

4.1 Wind system

The house is situated on a hill 210 metres above sea level and the average wind speeds at this height are shown in Fig. 9, with the minimum and maximum values of 6.1m/s and

11.4m/s, for August and October, respectively. While the original height at which the wind speed data was obtained is 10m according to NIWA [16], it is obvious that the wind speeds at height 210m are about twice the value of the initial wind speeds presented in Fig. 5, because of the height correction factor [22] introduced by equation (2). The wind speeds at height 210m are used in selecting the wind turbine, and a 2.5kW wind generator (Proven 7 type) is selected with a cut-in speed, rotor diameter and survival wind speed of 3.5m/s, 3.5m and 70m/s, respectively [23, 29], which can offer an excellent performance with the wind speed regime of the site. This wind turbine is a 3-phase, downwind 3 bladed, self-regulating wind turbine system. It has no cut-out speed, thus, offering a continuous operation in all wind speeds at this location. This is because “the blades pitch and cone as the wind gets stronger, thus, protecting the turbine and allowing its continual operation during the fiercest of storms”. The survival wind speed capacity of 70m/s takes care of the maximum hourly wind speed of ~35m/s at 6m hub height, at the site, based on 2012 NIWA wind data. The average power delivered by the wind generator is estimated by equation (1) and it is presented in Fig. 10(a). The Annual Energy Production (AEP) data provided by the manufacturer is shown in Fig. 10 (b); a Reference Annual Energy of 4,700kWh is also specified by the manufacturer for a hub height wind speed of 5m/s [23, 29]. The hub height average wind speed of the site is 9.42m/s, and this corresponds to an AEP of ~14,500kWh.

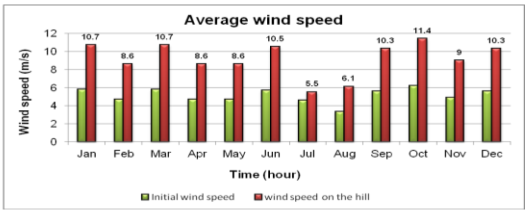

Fig. 9. Average wind

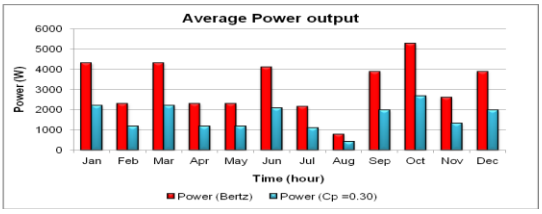

Fig. 10(a). Average power of the turbine

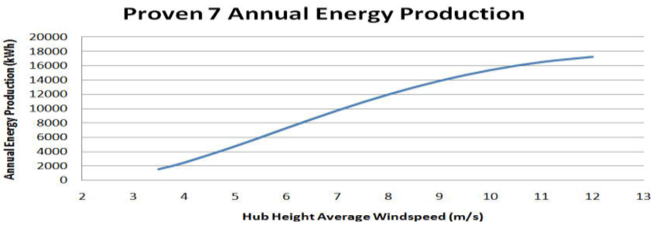

Fig. 10(b). Annual Energy Yield of the wind turbine

4.2 PV system

Four units of MITSUBISHI 250W monocrystalline modules have been sized for the application; the parameters of the modules are shown in Table 1 [30].

Performance at STC					
P_{max} (W)	V_{oc} (V)	I_{sc} (A)	V_{mp} (V)	I_{mp} (A)	η^{stc} (%)
250	37.6	8.79	31.0	8.08	15.1
Performance at NOCT					
P_{max} (W)	V_{oc} (V)	I_{sc} (A)	V_{mp} (V)	I_{mp} (A)	NOCT
180	34.2	7.12	27.9	6.46	47˚C

Table 1. Parameters of the PV module

The average power output and the efficiency of the PV array over the year are shown in Fig.11. It is obvious from the figure that the power outputs of the array during the summer months are higher than those obtained in the winter months; however, the efficiencies of the array during the summer months are lower than the values recorded during the winter months. This is due to the irradiance and temperature dependence of the PV modules. The efficiency at STC is 15.1%, but when the temperature is below 25˚C, the efficiency increases, as shown in Fig. 11, with a temperature coefficient of power of 0.0045/˚C [7]. The irradiance values during the summer months are more than those of the winter months, and the PV power outputs are not affected by the corresponding increase in the ambient and cell temperatures, for values within the limit ≤ 25˚C.

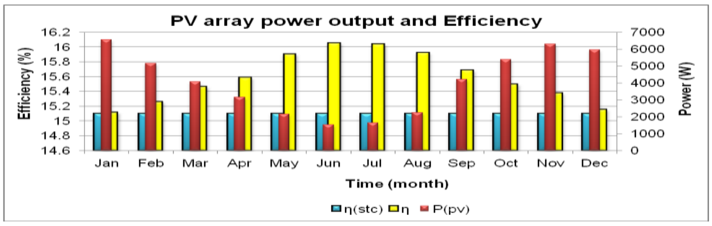

Fig.11. Average power output and efficiency of the PV array

4.3 Total renewable generation

The renewable power generated versus the daily load for one week in January and June is shown in Figs. 12 (a) and (b), respectively; the month of January and June have been selected to illustrate the seasonal variation in the renewable generation, i.e. for summer and winter periods, correspondingly. It can be observed that the PV power production is higher in January, compared to June. The daily average wind energy production from the analysis is about 32kWh, while an average energy yield of 3.79kWh/day has been recorded for PV system. These translate to about 11,685kWh/yr and 1,383kWh/yr yield, for wind and PV systems, respectively. In addition, there are some periods within the year when the wind speeds of the location are below the cut-in speed (3.5m/s) of the wind turbine; this situation accounts for the difference between the AEP of ~14,500kWh given by the manufacturer and the 11,685kWh/yr obtained from the analyses.

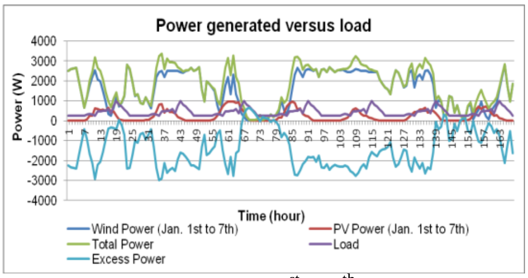

Fig. 12(a) January 1st to 7th

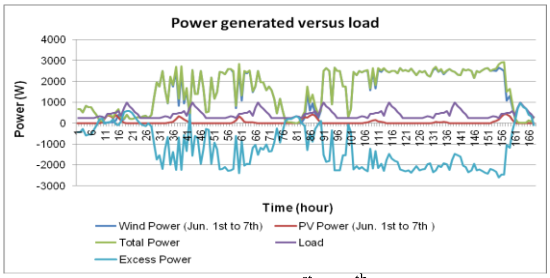

Fig. 12(b) June 1st to 7th

4.4 Battery system

The total average energy delivered is 35.79kWh/day (i.e. 32kWh plus 3.79kWh). The excess energy is obtained by deducting the average demand of 10kWh from 35.79kWh, which is 25.79kWh. This is stored by the battery system. A battery bank has been designed whose voltage is 24V and capacity of 1350Ah; its capacity translates to 32.4kWh, with 2 days autonomy, depth of discharge of 80% and 80% battery efficiency. This leads to the arrangement of 12 units of 2V 675Ah Exide battery cell in series, and then connecting them in 2 strings.

4.5 Generator

The generator is operated when the available energy (total generation plus the battery energy) is less than the load demand, which can also support additional loads such as pressing iron and photocopy machine. The size of the generator used for this application is 5.5kVA.
The hybrid system is shown in Fig. 13. The labels (a), (b), (c), (d) and (e) represent the house, wind turbine, HES components in the power room, single battery bank and generator,

respectively. The hybrid controller controls and manages the system, i.e. maintaining the battery state of charge at an acceptable level by coordinating the charging current from the wind and generator, and also managing the energy supply from the battery to the load when the wind/PV supplies are low or not available [24].

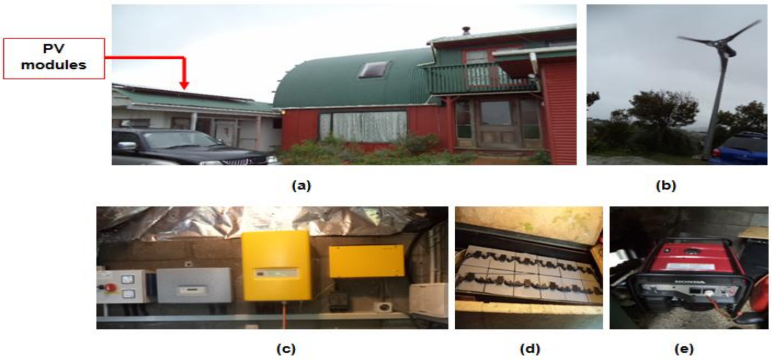

Fig. 13. The HES system

4.6 Economic aspect

The results of the LCCA are shown in Table 2, 3 and 4. It is seen from the results that scenario 1 (generator only) is more expensive than scenarios 2 and 3, in terms of C_r, *LCC*, *ALCC* and *COE*, even though its initial capital cost (C_{ic}) is the lowest. This is as a result of the high fuel and maintenance costs incurred over the project life. Scenario 2 (Wind/PV/Battery) is the priority energy option, and it has the least costs, amongst the three configurations. Scenario 3 (Wind/PV/Battery plus Gen) is applied when scenario 2 is not enough to support the load, and/or when there is need to use appliances with a higher power rating such as pressing iron, printer/photocopier etc; it is also cost-effective than scenario 1 even with the assumption that the generator consumes 2 litres of fuel per day. The fuel cost of scenario 1 has been reduced by 85% in scenario 3, over the project life.

Scenario 1 - Generator only			
Component	**Units**	**Cost/unit (NZD)**	**Total Cost (NZD)**
5.5kVA Generator	1	3,500	3,500
Installation	Lot	Lot	350
O and M	Lot	175	3,877
Fuel	13.6	9,928/year	222,043
C_{ic}($)			3,850
C_r($)			14,152
LCC ($)			254,225
ALCC($/yr)			19,887
COE($/kWh)			0.5504

Table 2. Results of the LCCA (scenario 1)

Scenario 2 - Wind/PV/Battery only			
Component	**Units**	**Cost/unit (NZD)**	**Total Cost (NZD)**
2.5kW Wind system	1	23,000	23,000
1kW PV system	1	750	3,000
2V 675Ah Battery	24	416.67	10,000
Installation	Lot	Lot	16,000
C_{ic}($)			52,000
C_r($)			8,675
LCC($)			61,783
ALCC($/yr)			4,833
C_{oe}($/kWh)			0.3698

Table 3. Results of the LCCA (scenario 2)

Scenario 3 - Wind/PV/Battery + Gen

Component	Units	Cost/unit (NZD)	Total Cost (NZD)
2.5kW Wind system	1	23,000	23,000
1kW PV system	1	750	3,000
2V 675Ah Battery	24	416.67	10,000
5.5kVA Gen system	1	3,500	3,500
Installation	Lot	Lot	16,350
O and M		225	4,985
Fuel	2	1460/yr	32,653
C_{ic}($)			55,850
C_r($)			11,712
LCC($)			104,092
ALCC($/yr)			8,143
COE($/kWh)			0.4766

Table 4. Results of the LCCA (scenario 3)

4.7 Environmental aspect

The minimum fuel saved is 11.6 litres per day, while the maximum quantity saved is 13.6 litres per day. These are obtained when scenarios 3 and 2 are used, respectively. Though these values could vary due to changes in the demand of the household, they provide indications of the potential of the HES to offer an environmental benefit. The household is being powered by a generator between 1997 and 2010. The 2.5kW wind turbine was installed in 2010, while the PV system was installed in 2011.

5. Implementation challenges

- Perception of the people: while some neighbours welcome the wind turbine system, others see it as disturbance. Their contention being the issue of noise. However, this issue was resolved by the fact that the houses in this area are sparsely located.
- Permission from local authority: this aspect needed to be settled before the implementation of the system could take place.
- Transportation: movement of materials to the site during construction of the wind turbine system was another challenge. This was however addressed by creating paths along the bush to the hill to ease the movement.

6. Conclusion

In this study, we have presented the development of a stand-alone hybrid renewable energy supply for residential use, using an off-grid household located on top of a hill in Brooklyn, Wellington as a case study. We present the technical and economic considerations for the energy system that can support a peak daily demand of about 10kWh, with the available wind and solar energy resources of the location. While scenario 2 (Wind, PV and Battery) is considered as the priority option, scenario 3 (Wind, PV, Battery and Generator) is used when the scenario 2 is not sufficient to meet the load demand and/or when there is need to operate appliances with a higher power rating such as pressing iron, printer/photocopier etc. We use Life Cycle Cost Analysis (LCCA) to compare the economics of scenario 2 and scenario 3 with scenario 1 (Generator only), in order to investigate the cost benefits. Results reveal that scenario 2 gives the least life cycle cost and the cost of energy, over the project life of 25 years. The inclusion of generator to this configuration when the need arises is also found to be cost-effective, compared to complete reliance on generator by the household. The fuel consumption has been reduced by the application of renewable energy system. Some implementation challenges of the system have also been articulated in the paper. The lessons learned from the design and analyses presented in this work could be used in developing off-grid renewable energy systems in other parts of Wellington, thus leading to widespread use of renewable technologies in the residential sector of the country.

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