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Sustainable Renewable Electricity for Small Islands: A Methodology for Essential Load Matching

Abstract

Renewable energy integration into diesel generation systems for remote island communities is a rapidly growing energy engineering field. Fuel supply issues are becoming more common and the disruption, instability and panic caused by fuel shortages results in inefficient and unreliable power supplies for remote island communities. This paper explains an energy engineering approach for providing renewable energy development, supply security, cost and sustainability objectives. The approach involves adapting proven energy engineering techniques including energy auditing, energy system modelling with basic cost analysis and demand side management. The novel aspect of this research is development of critical load engineering in the system design, and informing this with assessment of essentiality of energy services during the audit phase. This approach is motivated by experiences with previous fuel shortages and long term sustainability policy drivers. The methodology uses the most essential electric loads as the requirement for sizing the renewable energy capacity in the hybrid system. This approach is revolutionary as communication with the customers about availability and the need to shed non-essential loads both helps to meet cost and security requirements, and helps to reduce panic and uncertainty when fuel supply issues arise.

1. Introduction

Sustainability of a regional energy system is a complex design and behaviour problem (Krumdieck and Sohel 2007; Gyamfi, Krumdieck et al. 2008; Krumdieck and Dantas 2008). Small island communities highlight the requirements for strategic analysis of energy systems (Hamm 2007). Renewable energy resources are widely accepted as a sustainable energy solution (Lund 2005). However, renewable energy does not fit with current service and cost expectations, and availability will always impose limits on demand.

Small island states have sensitive environments with unique reliability challenges in reliability of electricity systems and transport services. Disruption of diesel fuel supply is a major concern. The remote islands in the Maldives currently generate all of their electricity from affordable, easy to operate and reliable diesel generator sets. The government has investigated renewable energy in response to continuously increasing trend in diesel fuel price and volatile international oil markets. Past events including the “Gulf Wars” and the 9/11 bombing caused diesel supply shortages which led to widespread load shedding and power cuts. The objective of this research is to design and develop island power systems which are capable of providing essential loads under unstable circumstances. This paper presents a methodology for hybrid electric power supply system design for islands. The key novelty of the approach is determining essential loads from village energy audits, sizing the renewable capacity to meet these loads, and making end-user communication part of the design.

2. Essential Load Matching Methodology

The present system has faced constraints in diesel fuel and future risks of disruption are increasing. Demand has been increasing rapidly with the introduction of new appliances. The government wants to develop renewable energy resources, but contain costs. The residents of villages on islands in the Maldives have a good standard of living, but are not wealthy by western standards. These design considerations have been addressed in the methodology by starting with an energy activity survey of the island. Figure 1 shows a schematic of the system design method. The electrical loads of the people of the community are characterised into three groups according to their essentiality :(a) Optional, (b) Necessary and (c) Essential according to answers given in surveys and discussion groups. After categorizing all of the loads, utilisation timing (pattern) of the appliances in each of the three categories are generated. The essential primary load includes the electrical loads that must be met immediately in order to avoid unmet load of activities that are essential to wellbeing. Deferrable loads are defined as those which need to be supplied sometime during the day or week but which can be deferred in time. These two loads were separately treated to generate representative load curves for each category. This way of load categorisation makes it easier to identify the levels of resiliency towards constraints. Several configurations of possible hybrid diesel/renewable system concepts are developed using available renewable resources.

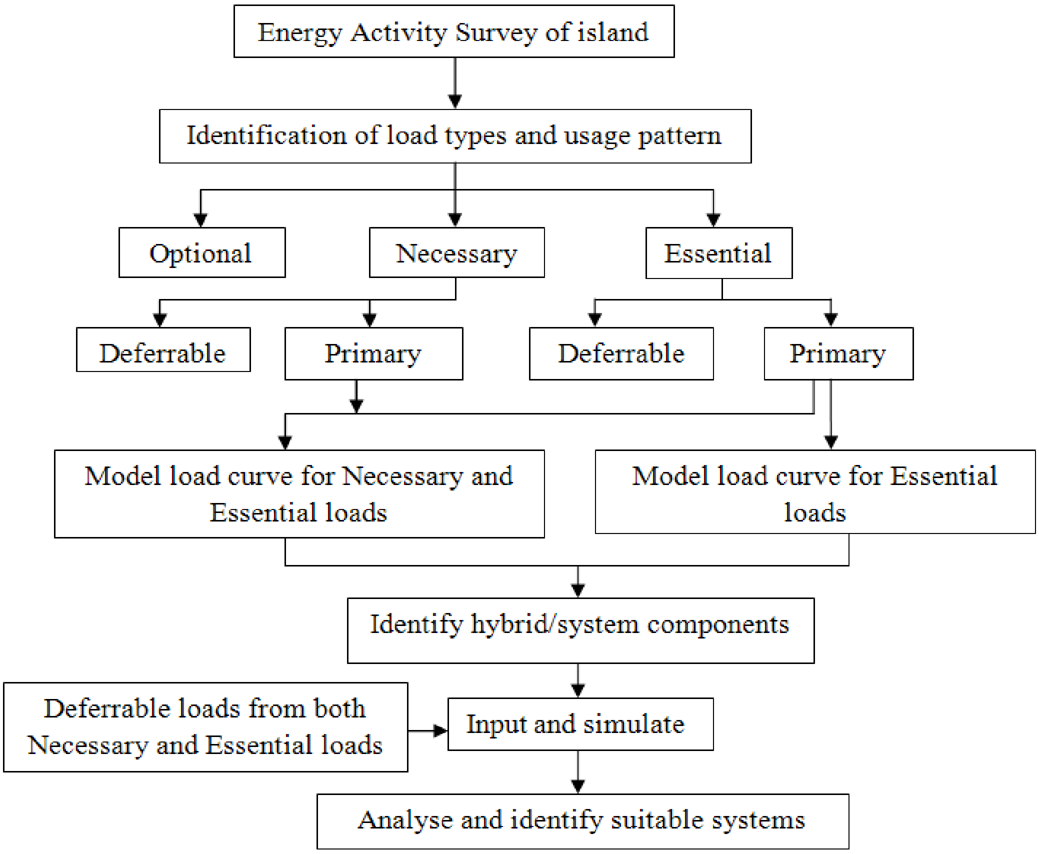

Figure 1 Overview of methodology to model the required load curves and design the system components, controls and communication systems

Economic and technical feasibility assessment of each concept system design is carried out using the HOMER modelling package. The best possible system configuration with the capability to provide the essential loads using renewable energy alone is selected as the system to be implemented for the future.

3. Case Study

Figure 2 shows an aerial view of Fenfushi, where the study was conducted and a view of the four diesel generator sets in the island powerhouse. Fenfushi is situated in the south west corner of the South Ari-Atoll, 110 kilometres from the capital, Malé. During the survey period, the island had a resident population of around six hundred, which remains fairly constant throughout the year. There were 78 households and public institutions, such as a school, administrative offices, a health centre and some shops.

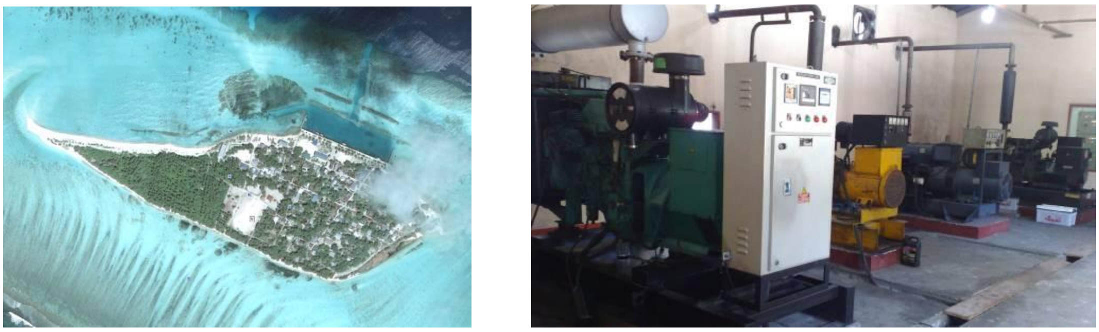

Figure 2. Google Aerial view of the island of Fenfushi in Maldives and the diesel generators at the powerhouse.

3.1 Electricity System

The island has a mini grid and electricity is currently provided by diesel generator sets shown in Figure 2. Electrical generation capacity consists of one 40 kW, two 60kW and one 160kW diesel generators. However, there was no synchronisation mechanism to run the generator sets simultaneously. At the time of the audit, only two (60 kW and 160 kW) of the generator sets were in working condition. The generators consume approximately 112,000 litres of diesel fuel per year (2007/2008). It costs about US $135,000 for diesel fuel only. The island has a flat selling rate of US $0.4 per kWh. Consumer charges do not cover the full cost of electricity generation and distribution, which is subsidised by the Government. The peak loading occurs in the evenings between eight and nine o'clock when most of the lights and electric fans are in use and while most people use their television sets. The smaller 60 kW generator set is used to meet low day-time loads and during the hours of high load, the larger 160 kW generator set is used. The switch between the generators is done manually.

3.2 Load Pattern

Figure 3 shows the load curves for the island. The "present curve" is the actual demand of a typical day measured during the energy audit. The 48 kW evening peak is mainly from the households and communal lighting with about 4.6 kW contributed by the street lights. The main contributors to the morning peaks were electric fans and small water pumps. During the day time the demand is much lower as most of the people are at work and in many households most of the appliances such as lights and fans were switched off. The electricity supply has been “relatively reliable” though occasional power failures occur for few minutes at a time and voltage drops as the network runs further away from the power house.

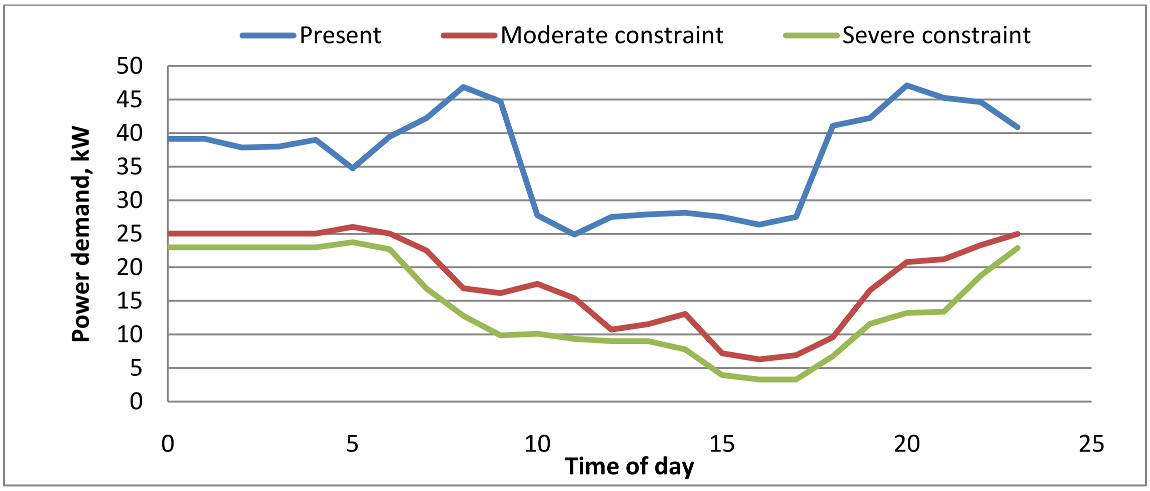

Figure 3. Electric load curves for the community showing a typical day load profile and loads modelled for moderately and severely constrained scenarios.

The two lower demand curves were modelled, one for moderate constraints in supply and the other for severe supply constraints. The moderately constrained curve was modelled by omitting the loads considered optional by the residents and the severely constrained curve was generated by omitting optional and necessary loads. In both the cases, deferrable loads were identified from the primary loads. In modelling with HOMER, the software requires primary and deferrable loads to be treated separately to find the optimised solution in terms of NPC (Net Present Cost) for the given variables.

4. HOMER Simulation

HOMER can be used for the comparison of power generation technologies across a wide range of applications. HOMER models physical behaviour of and its life-cycle cost. Constraints and ranges of variables can be investigated for sensitivity of NPC (Lambert, Gilman et al. 2006). HOMER can accept hourly time-step load and environmental data inputs, providing detailed modelling of the time span examined, while still allowing assessment of multiple simulations (Lambert, Gilman et al. 2006).Two main investigation steps in carrying out successful HOMER simulations are the system’s technical feasibility in meeting the specified load demand and optimisation of the various configurations based on NPC of the system, which is the total cost of installing and operating the system over its lifetime (Dalton, Lockington et al. 2009).

For this analysis, a battery ‘cycle charging’ strategy was used as it increases battery longevity by maintaining the state of charge at required levels (Dufo-López and Bernal-Agustín 2005; Dufo-Lopez, Bernal-Agustín et al. 2007). The ‘capacity shortage’ is the percent of the total load plus operating reserve that the system fails to supply in a given period, normally an annual value. This shortage can also be referred to as an allowable blackout of the system. Results for 15% shortage levels are presented in this paper for present load demand.

The operating reserve constraint was set at 10%. This is the additional reserve capacity required for a system to account for sudden increases in the electric load or sudden decreases in the renewable power output. Higher reserves of 25% for PV (photovoltaics) and 50% for wind turbines (WT) were set for the renewable output. These higher levels are required due to the inherent variability in the output of the chosen renewable energy sources.
The analysis and design of power systems can be challenging, due to the large number of design options and the uncertainty in key parameters, such as load size and future fuel price. Renewable power sources add further complexity because their power output is often intermittent as the availability of renewable resources may be uncertain.

One of the powerful features of HOMER is its ability to do sensitivity analyses on hourly data sets such as the electric load and energy sources. In this analysis the three loads were treated separately rather than using as sensitivities but the number of wind turbines (WT), PV panels and diesel generators (DG) were considered in the sensitivity analysis for the three load curves and with each simulation the recommended supply options are created in graphical forms and this helps energy planners to decide what type of power system components to use for different communities based on the load size and average renewable resources of the community.

5. System Configurations

Different system configurations were simulated for the three demand curves to find the most appropriate system for each. Figure 4 illustrates system configurations connected to either the alternating current (AC) or direct current (DC) buses depending on the components of that particular system, e.g. wind turbines could be either AC or DC. Both AC and DC wind turbines were considered in this analysis but most of the chosen systems result with AC turbines. PV and battery modules connect to the DC bus and a converter (inverter, rectifier or both) links both AC and DC buses.

All hybrid systems were modelled as parallel configurations as seen in figure 4 as this allows synchronous bi-directional power flow between battery bank and AC generators, reducing the risk of power supply breaks (Dalton, Lockington et al. 2009). The main advantage of parallel configuration is in allowing the AC components (wind turbine and diesel generators in this case) to directly supply the load; this achieves greater efficiency since it doesn’t have to be routed through a converter and battery.

For all systems, configurations the most appropriate components were selected from a large number of simulations. A wide range of component sizes were used in simulations for design selection. Initial costs and replacement costs of components were chosen from data collected from local dealers, international suppliers and peer reviewed papers. Electrical load data for each of the cases was put into HOMER software, which uses its randomising algorithms to compile a full-year load profile for each of these scenarios. The average solar irradiance values for Fenfushi are 5.31 kWh/m^2/day. This value is above average in comparison to many other locations around the globe (Cano, Monget et al. 1986),(Davies, Schertzer et al. 1975),(Dalton, Lockington et al. 2008). Wind speed data from the central weather station of Maldives was used. The average wind speed measured for the location was 4.7 m/s. which is comparable to average wind speeds from several other locations around the globe (Archer and Jacobson 2005). Figure 5 and figure 6 shows the monthly average solar radiation and wind speed of the location respectively.

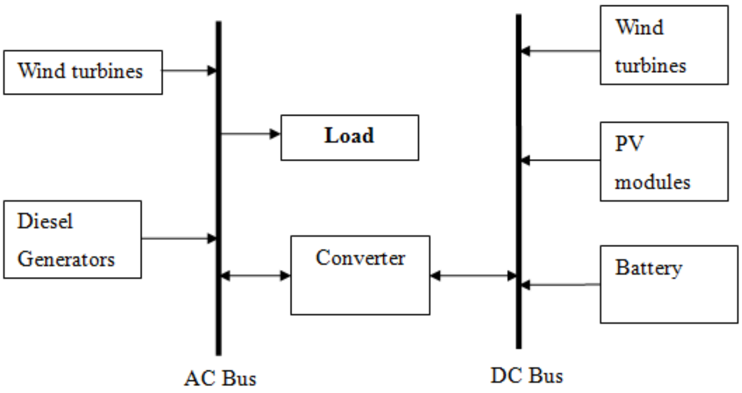

Figure 4. Typical hybrid-electric system configuration with diesel generators and renewable sources.

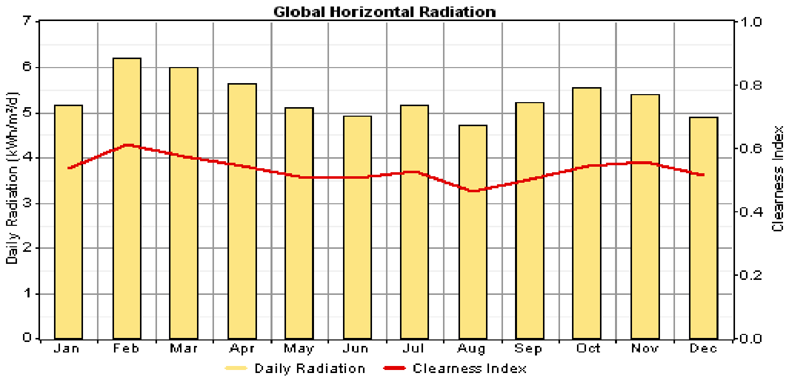

Figure 5 Monthly average solar radiations of the location

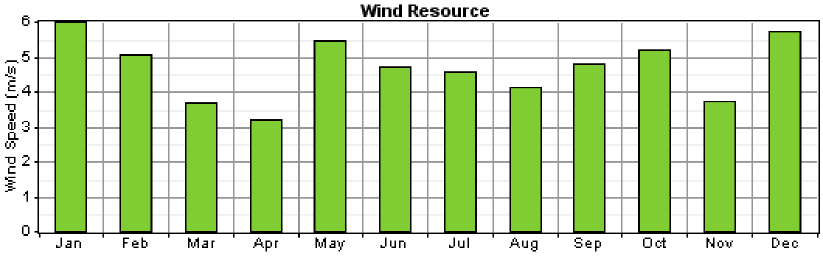

Figure 6 Monthly average wind speed of the location

A life span of twenty years for PV arrays, fifteen years for wind turbines and 20,000 hours for diesel generators were considered in the simulations. After several trial simulations with different wind turbines, the most appropriate wind turbine for the case study came to be WES- 5 Tulipo with a rated power of 2.5 kW AC generator. Basic specifications for PV panels were used for the HOMER simulations. The cost of the present diesel generators were not taken as an investment as the newest diesel generator has been in use for more than three years and soon this will require a major overhauling or replacement and this will require a significant capital investment as many components need to be replaced. In addition, these diesel generators are not the appropriate size generators as indicated from the simulations. Training for two operators for any of the systems containing renewable sources and maintenance cost for the systems have been included in carrying out the simulations.

6. Results and Analysis

Figure 8 and figure 9 are both for the final chosen hybrid system with minimum renewable energy to meet the essential load but considering diesel to supplement the present load. A variety of design parameters such as PV size, wind turbine sizes and numbers, battery capacity have been considered.

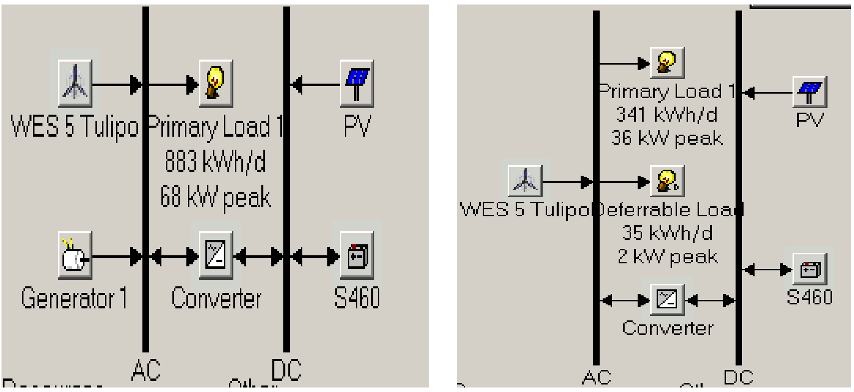

Figure 7. HOMER diagrams for system configuration for the hybrid PV-wind-diesel-battery set up for present load and all renewable generation sources for Essential loads.

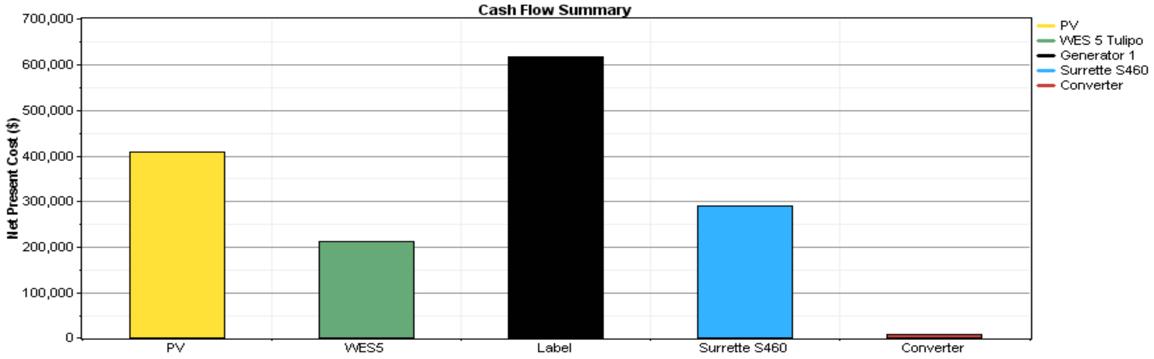

Figure 8. Cash flow summary of the selected system for present load but with renewable sources capable of providing the entire essential load of the island

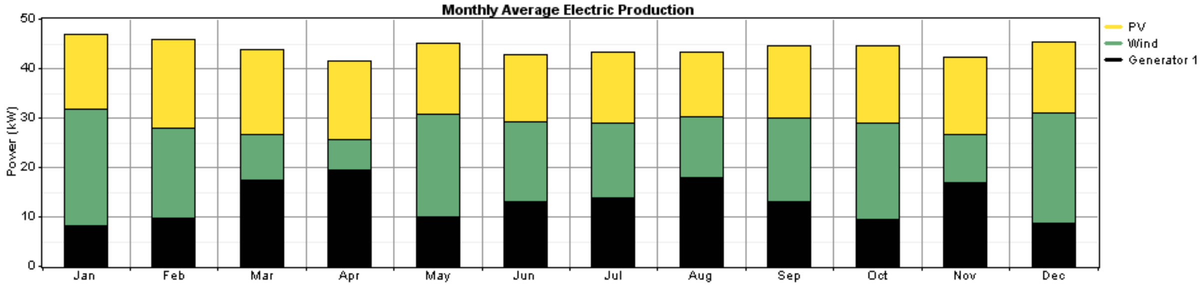

Figure 9. Monthly average electricity productions from the selected system for present load but with renewable sources capable of providing the entire essential load of the island.

Diesel price was set at 1.2 $/litre, the price at the time of survey. The interest rate was taken as 6% and the project lifetime was 25 years.

Present load

For simulations with the present load curve, capacity shortages of up to fifteen percent were allowed to see the competitiveness of the systems as there were a significant amount of optional loads. Another reason for giving this allowance was to observe the frequency and pattern of unmet load occurrences throughout the year. From the hourly analysis data it was evident most of the unmet load occurrences have been during the months of low average wind speeds for systems with wind turbines and the shortage never exceeds more than seven hours continuously in any given day of the year for any of the system configuration concepts. The system with the lowest NPC to meet the present demand was a hybrid system of wind turbines, PV, diesel generator and battery (see table 1 for system component sizes). The NPC was $1,346,943. The Cost of Energy (COE) was $ 0.33/kWh and the renewable energy contribution was 58% with 61,660 kWh of excess energy per year.

Comparing the diesel-only system with a 100% renewable system, the NPC of the renewable system was 8.3% higher but there was no significant variation in the cost of energy (COE). Allowing a 5% shortage in the capacity, the renewable system becomes more attractive in terms of both NPC and COE. Unlike the diesel system, the renewable system (with lowest NPC) can provide excess energy that could be used for water desalination. Results show a large amount of excess energy with the RE system, sufficient to provide fresh water for the whole community. This is an important consideration as water quality of the ground water is becoming unusable. It is highly likely that in the near future a desalination plant would be commissioned in this island as some few other islands have done recently.

Essential load

100% renewable energy systems to supply the essential load shows that the PV- battery and PV-wind-battery systems have higher COE (more than 0.5 $/kWh) even though they have lower NPC as expected (see table 2). For hybrid systems with diesel generators, both the NPC and COE results were lower than any of the systems with 100% renewable sources. The chosen system with all renewable sources was PV-wind and battery (capacity of the system elements are shown in table 3) with NPC of $884,194 and COE $0.51/kWh. The system's initial investment was $645,998 with 112,684 kWh of excess energy per year.

The final selection

The minimum renewable energy sources to supply the essential loads of the community were simulated with diesel generators to find the optimal supply mix for the present load. The final outcome has the following characteristics; NPC and COE were $1,532,340 and $0.37/kWh respectively, lower than any diesel-only systems that could supply the demand. The total annual electricity production is 386,444 units (kWh) of which 9.61% is excess electricity and annual operating cost is $68,688. Compared to the diesel-only systems there is a fuel savings of 77,021 litres of diesel per year which is a 66.5 % reduction. Annual carbon dioxide emission reduction of 202,824 kg achieved which is a reduction of 66.5%. Annual renewable energy contribution of 70% would be achieved of which 34% from PV arrays and 36% from wind turbines.

Table 1.Overall results for present electric load demand. Grey rows are with no shortage and white rows are with fifteen percent shortage allowed

System	PV (kW)	WT (Nos)	DG1 (kW)	DG2 (kW)	Total NPC ($)	Initial capital ($)	COE ($/kWh)	RE (%)
PV-battery	305	-	-	-	2,660,692	1,868,782	0.646	100
	225	-	-	-	1,812,513	1,306,398	0.504	100
DG	-	-	41	56	1,840,256	16,621	0.447	0
	-	-	3	34	1,606,688	12,394	0.425	0
DG-battery	-	-	13	37	1,793,908	22,485	0.436	0
			6	31	1,620,839	15,712	0.430	0
WT-PV-battery	185	42	-	-	1,992,582	1,446,998	0.484	100
	55	43	-	-	1,133,855	787,282	0.311	100
WT-DG-battery	-	31	0	-	1,347,327	322,017	0.327	59
	-	33	20	-	1,177,537	374,000	0.318	71
WT-PV-DG-battery	0.6	30	40	-	1,346,943	327,794	0.327	58
	1.2	38	15	-	1,123,229	501,027	0.305	82

Table 2.Overall results for Essential load demand

System	PV (kW)	WT (Nos)	DG1 (kW)	DG2 (kW)	Total NPC ($)	Initial capital ($)	COE ($/kWh)	RE (%)
PV-battery	140	-	-	-	1,177,999	837,048	0.672	100
DG	-	-	20	12	816,037	11,964	0.465	0
DG-battery	-	-	16	8	953,179	97,039	0.544	0
WT-PV-batt	85	18	-	-	884,194	645,998	0.505	100
WT-DG-battery	-	20	25	-	648,717	288,275	0.370	81
WT-PV-DG-battery	0	20	25	-	649,174	283,775	0.370	81

Table 3. Chosen (lowest NPC) system results for the present load having minimum renewable energy sources capable of supplying the essential loads without any unmet demand

System	PV (kW)	WT (Nos)	DG1 (kW)	Total NPC ($)	Initial capital ($)	COE ($/kWh)	RE (%)
WT-PV-DG-batt	85	18	40	1,532,340	654,283	0.372	70

7. Conclusions

The results show various levels of renewable capacity depending on the system components and constraints chosen. The simulation results and analysis show that there were no 100% renewable systems that can meet present demand at a realistic cost. Either the system was too expensive or there were too many generation components for the available land area (often available land is constrained in these islands). The minimum renewable system components identified to serve the essential load with diesel generators results in a solution for these islands with lower NPC and COE values compared to diesel only generation.

Considering the emission levels of pollutants such as CO_2, CO, SO_2, and NO_x, the final selected hybrid system emits much less than a diesel-only system (details are not included here) and risk of supply interruptions are reduced. Under the circumstances considered the results show realistic potential and feasibility of incorporating renewable sources to meet the essential load (see table 2 and 3). Applying the methodology to the case study provides a feasible solution with over seventy percent of annual generation from renewable sources. The system is also capable of meeting all essential loads without diesel generation throughout the whole year with no capacity shortages or unmet load. It is important to note that the resulting system configuration is well suited to the environment of these islands and the economics is favourable compared with diesel-only systems (see tables 1, 2 and 3).

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