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Optimal planning and design of a renewable energy based supply system for microgrids

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ABSTRACT

Renewable energy sources are gradually being recognized as important options in supply side planning for microgrids. This paper focuses on the optimal design, planning, sizing and operation of a hybrid, renewable energy based microgrid with the goal of minimizing the lifecycle cost, while taking into account environmental emissions. Four different cases including a diesel-only, a fully renewable-based, a diesel-renewable mixed, and an external grid-connected microgrid configurations are designed, to compare and evaluate their economics, operational performance and environmental emissions. Analysis is also carried out to determine the break-even economics for a grid-connected microgrid. The well-known energy modeling software for hybrid renewable energy systems, HOMER is used in the studies reported in this paper.

1. Introduction

With the price of oil reaching its highest levels and the costs of transmission line expansion rapidly increasing, combined with the desire to reduce carbon dioxide emissions, renewable energy has become an important alternative as a power provider in rural systems. The cost of energy from conventional sources is less than that from renewable energy sources, but a supply-mix of renewable energy and diesel can reduce the cost of energy [1].

Energy demands are increasing rapidly, requiring energy resources to meet these demands, resulting in an exponential increase in environmental pollution and global warming. On the other hand, these days renewable energy, which is clean and limitless sources of energy, is catching the attention of energy developers. However, the estimation of the correct type of renewable energy system needs to be done under optimizations technique. In addition, for remote, rural isolated power systems, renewable energy sources are being increasingly recognized as cost-effective generation sources. In isolated areas, the high cost of transmission lines and higher transmission losses are encouraging the use of green sources of energy. Combining two or more renewable energy sources, such as solar, wind, hydro, diesel, etc., together gives a stable energy supply in comparison to non-renewable energy systems. Several studies have been done to evaluate the optimal hybrid renewable system for isolated systems, as mention below.

Particle Swarm Optimization (PSO) technique is applied in [2] to locate the optimal number of PV modules installed, such that the total net economic benefit achieved during the system operational life is maximized. In [3] it has been brought out that a wind/PV/diesel hybrid system implemented in three remote islands in Maldives provide very good opportunities to showcase high penetration of renewable energy sources. In [4] a feasibility analysis considering off-grid stand-alone renewable energy technology systems for remote areas in Senegal show that the levelized electricity costs with renewable energy technology is lower than the cost of energy from the grid extensions. In addition, the renewable energy technologies have a friendly impact on the environment.

In high rainfall areas near to rivers which flow all year round, solar and wind energy systems should be considered only after careful consideration of installation strategies. On other hand, water power should be considered as an option for electricity generation in these remote areas. In [5] the use of micro-hydro power is proven, and has gained favor in remote area electrification instead of diesel generation, but it requires significant head. In [6] the authors develop an optimum sizing methodology to determine the dimensions of a hybrid energy supply system, while minimizing the capital cost. It is seen that the most attractive energy supply solution for the support of remote telecommunication stations is the proposed hybrid power system comprising pv, diesel, inverter and batteries.

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In Ref. [7] a Mixed Integer Linear Programming (MILP) model is proposed for optimal planning of renewable energy systems for Peninsular Malaysia to meet a specified CO_2 emission reduction target. Mizani and Yazdani in [8] demonstrate a mathematical model and optimization algorithm as well as use the HOMER software [9] to identify the optimal microgrid configuration and their optimal generation in the mix. The results show that optimal selection of renewable energy sources and energy storage devices in a grid-connected microgrid, in conjunction with an optimal dispatch strategy, can significantly reduce the microgrid lifetime cost and emissions.

The authors in [10] discuss ways to reduce fuel usage and hence minimize CO_2 emissions while maintaining a high degree of reliability and power quality for microgrids. This is achieved by maximizing the utilization of renewable resources, dispatching and scheduling the fossil fuel generators at their optimal efficiency operating points, by storing excess energy in a storage system, while reducing the dependency on the utility grid. A methodology for microgrid village design and its economic feasibility evaluation with renewable energy sources is proposed in [11].

The economic operation of a combined heat and power (CHP) system consisting of wind power, PV, fuel cells, heat recovery boiler, and batteries is discussed in [12], using a non-linear optimization model. Forecasting of 24-h, wind speed, solar radiation, heat and electricity demand is considered on as well. The optimal operation of a microgrid comprising wind power, PV, and battery, discussed in [13], using a heuristic algorithm and linear model, and test results indicate that effective use of batteries can reduce the operating costs.

The off-grid electrification by utilizing Integrated Renewable Energy System (IRES) is proposed in [14] to satisfy the electrical and cooking needs of seven non-electrified villages in India. Four different scenarios are considered during modeling and optimization of IRES to ensure reliability parameters. The National Renewable Energy Laboratory (NREL) provides information to the community on hybrid renewable energy and microgrid power systems, presents lessons learned from operational experience, and provides analysis of challenges and success of the assessed systems [15]. A comparative analysis between diesel, hydro-diesel, and photovoltaic-diesel technologies is presented in [16] to analyze the field performance of different off-grid generation technologies applied to the electrification of rural villages. The relevance of distributed generation in India is discussed in [17]. The paper elaborates on the initiatives in the islands of the Sundarbans region in India and reviews microgrids in light of the emerging technologies suitable for small islands.

The planning of microgrid in rural areas, considering renewable energy sources, requires the definition of several factors, such as: the best sources of renewable energy to be used, the number and capacity of these generation sources, the total system cost, the amount of emissions that can be saved, the distance from the nearest grid connecting point, the excess energy, unmet load, diesel prices, different loads, and grid-connected systems. In addition, in many countries governments strongly encourage the planners of microgrids to be motivated towards investment in the renewable energy sector. In this paper, all of the above factors, as well as their effect on the proposed system, are examined. The main objectives of the work can be outlined as follows:

- Optimal design and planning of a renewable energy based microgrid considering various renewable energy technology options and with realistic inputs on their physical, operating and economic characteristics.
- To determine the break-even distance for connection of the microgrid with the main grid, and compare that with the cost of the isolated microgrid.
- Compare the overall benefits from the optimally designed renewable energy based microgrid with existing microgrid configurations.

The rest of the paper is organized as follows: Section 2 presents the problem definition, Section 3 briefly discusses the system under consideration and the system input data, Section-4 gives a brief description of the HOMER simulation tool and its capabilities, in Section 5 different study cases considering the optimal microgrid design is carried out and the results are presented and discussed, and finally Section-6 presents the summary and conclusions of this work.

2. Problem definition

The two principal economic elements, which are the total net present cost (NPC) and the levelized cost of energy (COE), depend on the total annualized cost of the system. Because of that, the user needs to calculate the annualized costs of the system, which is the components' annualized cost minus any miscellaneous costs. To calculate the total net present cost the following equation was used:

$$C_{\text{NPC}=}\frac{C_{\text{TANN}}}{\text{CRF}_{(i,N)}} \tag{1}$$

where C_{TANN} is the total annualized cost, i is the annual real interest rate (the discount rate), N is the number of years, $\text{CRF}_{i,N}$ is the capital recovery factor, and it is calculated as a following equation:

$$\text{CRF}_{i,N} = \frac{i(1+i)^N}{(1+i)^{N-1}} \tag{2}$$

In addition, the following equation is used to calculate the levelized cost of energy:

$$\text{COE} = \frac{C_{\text{TANN}}}{E_{\text{ls}}+E_{\text{grid}}} \tag{3}$$

where E_{ls} is the electrical energy that the microgrid system actually serves and E_{grid} is the amount of electricity sold to the grid by microgrid. In the levelized cost of energy Equation (3), the total annualized cost is dividing by the electrical load that the microgrid actually serves. Also, in the levelized cost of energy equation the amount of electricity sold to the grid by microgrid is added. In HOMER, the total net present cost is the economically preferable element and has been used in the optimization process, not the levelized cost of energy, because each of these decisions is somewhat arbitrary [18].

In HOMER, the lifecycle cost of the system is sorted by the total net present cost (NPC). All the system costs, such as the capital cost, replacement cost, operation and maintenance cost, fuel consumption cost, and miscellaneous costs, for example, the credits that are caused by the pollutant emissions, and the grid cost (purchase power from the grid), are included in the total net present cost (NPC). The difference between the nominal interest rate and the inflation rate is equal to the real interest rate that has to be entered by HOMER's programmer. In addition, HOMER's programmer has to enter all costs into the system in terms of constant dollars [9,18].

3. System under consideration

The available energy supply options in the hybrid microgrid system design under consideration are wind turbines, solar PV array, battery bank, hydro turbines, diesel generator, dump load,

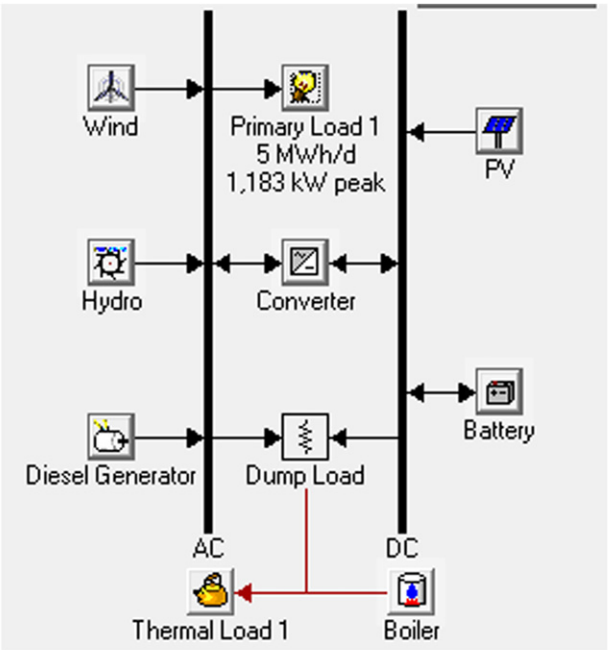

Fig. 1. Available portfolio of energy supply options in microgrid planning.

boiler and an AC/DC converter (Fig. 1). The characteristics and cost of the system components are presented in the following subsections.

3.1. Assumptions and model inputs

3.1.1. Electrical load

Fig. 2 illustrates the load profile of the proposed hypothetical rural community. The energy consumed by the community is 5000 kWh/day with a 1183 kW peak demand.

The data source is synthetic and 15% of daily noise and 20% of hourly noise is considered. The mechanism for adding daily and hourly noise is as follows. HOMER randomly draws the daily perturbation factor once per day from a normal distribution with a mean of zero and a standard deviation equal to the daily noise input value. In addition, it randomly draws the hourly perturbation factor every hour from a normal distribution with a mean of zero and a standard deviation equal to the hourly noise input value [9].

3.1.2. Thermal load

The thermal load is assumed to be 5% of the electrical load, as shown in Fig. 3. The scaled annual average is 500 kWh/d while the scaled peak load is 51.07 kW, with a load factor of 0.355. The idea of adding thermal load in this paper is to examine the impact of excess energy feeding the thermal load.

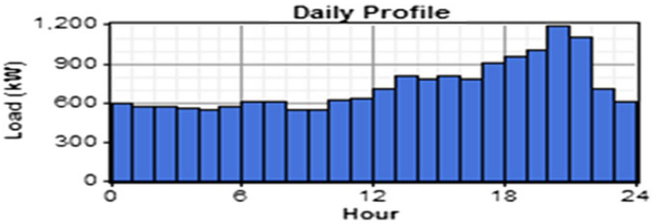

Fig. 2. Hourly electrical load profile of microgrid.

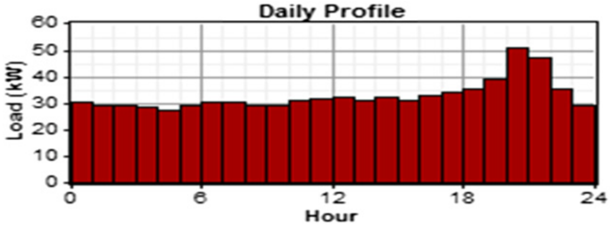

Fig. 3. Hourly electrical load profile of microgrid.

3.1.3. Solar resource

The solar radiation profile of Waterloo, Ontario, (43° 39′ N, 80° 32′ W) is considered for this work. Solar radiation data is obtained from the NASA Surface Meteorology and Solar Energy website [19]. The annual average solar radiation for this region is 3.64 kWh/m^2/day. Fig. 4 shows the solar radiation profile over a one-year period.

The capital and replacement costs of photovoltaic (PV) panels include shipping, tariffs, installation and dealer mark-ups. Some maintenance is typically required on the PV panels. A de-rating factor of 90% reduces the PV production by 10% to take in account the varying effects of temperature and dust on the panels.

3.1.4. Wind resource

The wind speed profile of Waterloo, Ontario, is considered for this work. Wind data for this region is obtained from the Canadian Wind Energy Atlas [20]. The annual average wind for this area is 5.78 m/s Fig. 5 shows the wind speed profile over a one-year period. Wind turbine capital cost and replacement costs include shipping, tariffs, installation, and dealer mark-ups. The hub height is 15 m.

3.1.5. Diesel price

The study includes a sensitivity analysis on the price of diesel, which can vary considerably based on region, transportation costs and current market price. Diesel prices of 0.30 $/L to 0.70 $/L are evaluated, with an emission density of 820 kg/m, carbon content of 88% and a sulfur content of 0.33%.

3.1.6. System economics

The annual real interest rate considered is 0.6%. The real interest rate is equal to the nominal interest rate minus the inflation rate. The project lifetime is 25 years. The model constraints include maximum annual capacity shortage, varying from 0% to 10%. The operating reserve is considered to be 10% of the hourly load, plus 50% of the solar and wind power output. Input data on option costs, sizing and other parameters are presented in Tables 1 and 2.

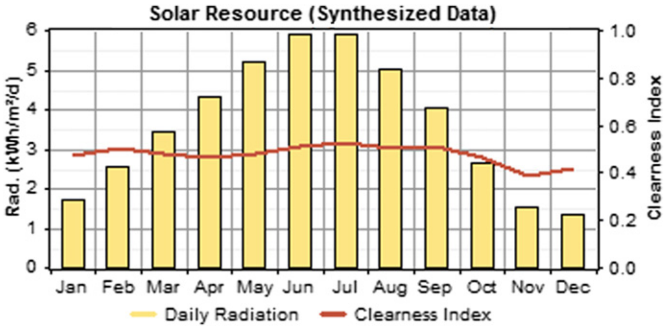

Fig. 4. Solar radiation profile for Waterloo.

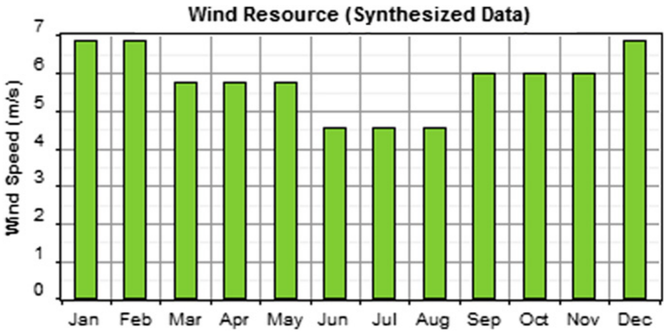

Fig. 5. Wind speed profile for Waterloo.

4. The hybrid optimization platform: HOMER

HOMER is a simulation tool developed by the U.S. National Renewable Energy Laboratory (NREL) to assist in the planning and design of renewable energy based microgrids. The physical behavior of an energy supply system and its lifecycle cost, which is the sum of capital and operating costs over its lifespan, is modeled using HOMER [18]. Options such as distributed generation (DG) units, stand-alone, off-grid and grid-connected supply systems for remote areas, and other design options, can also be evaluated using HOMER [9]. HOMER is designed to overcome the challenges of analysis and design of microgrids, arising from the large number of design options and the uncertainty in key parameters, such as load growth and future fuel prices. Simulation, optimization, and sensitivity analysis are the three principal tasks performed in HOMER [18].

4.1. Simulation

In the area of simulation, HOMER determines technical feasibility and lifecycle costs of a microgrid for each hour of the year. In addition, the microgrid configuration and the operation strategy of the supply components are tested to examine how these components work in a given setting over a period of time. The simulation capability of HOMER is the long-term operation of a microgrid. The optimization and sensitivity analysis of HOMER depends on this simulation capability [18].

4.2. Optimization

In the optimization section, HOMER displays the feasible systems with their configurations under the search space defined by the user, sorted by the minimum cost microgrid depending on the total net present cost. After the simulation finds out the system configuration of a microgrid, the optimization is calculated and displays the optimal microgrid configuration. HOMER defines the optimal microgrid configuration, which is that configuration with the minimum total net present cost and meeting the modeler's constraints [18].

Table 1
Input data on option costs.

Options	Capital cost	Replacement cost	O&M cost
Wind	$7900/turbine	$9000/turbine	$30/year
Solar	$7.50/W	$7.50/W	0
Micro-Hydro	$3600	$3600	$18/yr
Battery	$75/Battery	$75/Battery	$2/Battery/year
Converter	$1000/kW	$1000/kW	$100/year
Grid Extension	$20.000/km	$20.000/km	$10/year/km
Diesel Generator	For a 4.25 kW $2550	$2550	$0.15/h

Table 2
Input data on option sizing and other parameters.

Options	Options on size and unit numbers	Life	Other information
Wind	10, 50, 100, 500, 1000 turbines	15 yrs	Weibull distribution with k=1.83
Solar	1, 10, 100, 1000, 3000 kW	20 yrs	De-rating factor = 90%
Micro-hydro	500 L/s flow rate	25 yrs	Scaled annual avg = 50, 100, 150 L/s
Battery	1, 1000, 5000, 10,000, 15,000, 20,000	845 kWh	Nominal capacity 225 Ah
Converter	0,1,10,50, 100, 500,1000 and 2000 kW	15 yrs	Can parallel with an AC generator. Converter Efficiency = 90% Rectifier Efficiency = 85%
Grid extension	–	–	Price of Electricity = $0.14/kWh
Diesel generator	0 to 1500 kW	5000 h	Minimum load ratio = 30%

4.3. Sensitivity analysis

In this section, the modeler can analyze the effects of parameter variations with time. HOMER finds out the optimal values for the different sizes and quantities of the equipment that is considered in the microgrid and the associated constraints. The sensitivity variables are those variables which have been entered by the user and have different values. The main objective of using the sensitivity analysis in HOMER is that if the user isn't sure which is the best value of a particular variable, then the user will enter different values and the sensitivity analysis will show how the results behave dependent on these values. Many optimizations have to be performed in this section by HOMER, each using different values of input assumptions [18].

5. Results and discussions

In this section, four different cases are constructed in order to determine the most favorable option for microgrid planning as given in Table 3. In Case-1, the microgrid is assumed to be already in place, and is being supplied by an isolated network fed by diesel generators, as in the case of many remote power systems around the world that are dependent on imported fossil fuel to feed their demand. However, these units are very expensive because of their high cost of maintenance, fuel supply and fuel transportation. In addition, the diesel generators are highly emission intensive. Case-2 considers that the microgrid is entirely based on renewable energy sources, Case-3 is a mixed configuration comprising both diesel and renewable energy sources, while in Case-4 it is assumed that the microgrid has the option of connecting and drawing energy from the external grid.

5.1. Comparison of various cases

5.1.1. Optimal plan configurations and cost components

The optimal microgrid designs for the various cases considered are obtained from HOMER simulations, using the parameters as

Table 3
Summary of cases studied.

Case	Description of case
1	Diesel dependent microgrid (Base case)
2	Renewable-based microgrid (wind, solar PV, battery, micro-hydro, converter)
3	Diesel-renewable mixed microgrid (diesel, wind, solar PV, battery, micro-hydro, converter)
4	Microgrid-connected to external grid

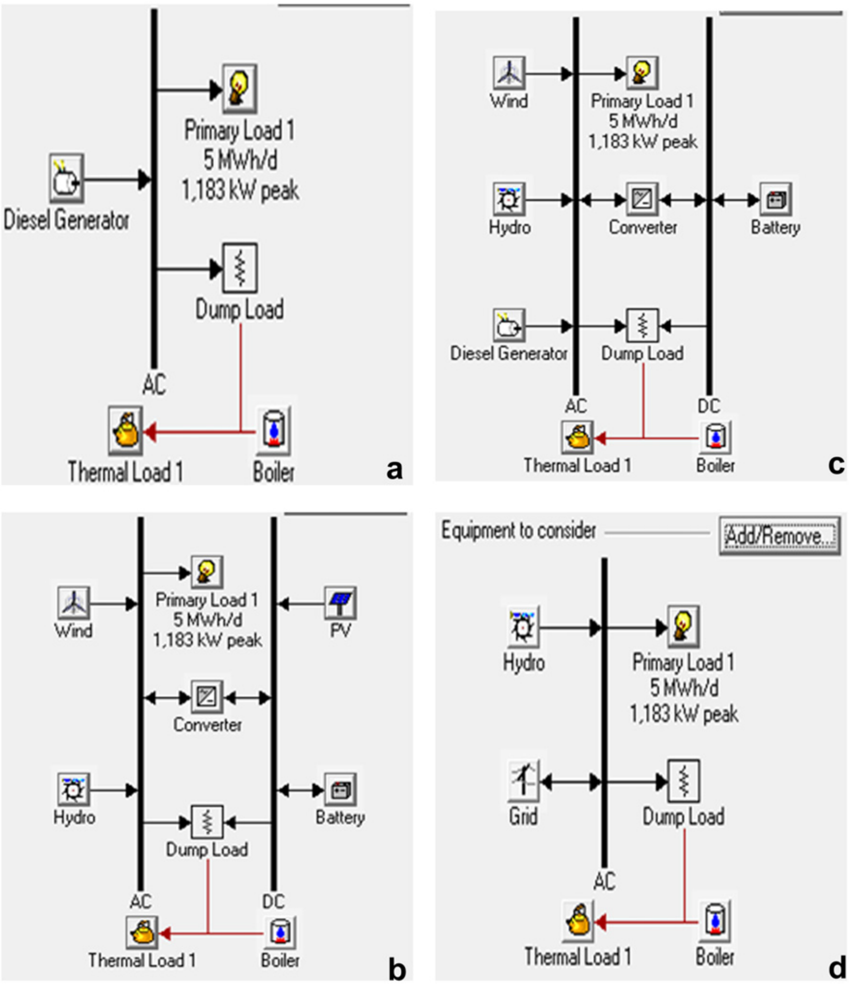

Fig. 6. Comparison of various optimal microgrid configurations. (a) Case-1, (b) Case-2, (c) Case-3, (d) Case-4.

described in Section 3. The optimal microgrid configurations for the four cases are shown in Fig. 6(a)–(d). The corresponding details of the optimal microgrid plans for each case are presented in Table 4.

As stated earlier, this work is aimed at finding the least-cost microgrid plan while taking into account the environmental impact of each plan obtained from various cases considered. From the optimal microgrid configuration obtained, as presented in Fig. 6 and Table 4, it is seen that while the diesel dependent microgrid (Case-1) selects 6375 kW of diesel capacity to meet its demand, the renewable-based microgrid (Case-2) completely relies on solar PV, wind, battery storage and micro-hydro generation. The diesel-renewable mixed microgrid (Case-3) opts for a reduced diesel generation capacity of 4250 kW and some renewable capacity. Finally, it is noted that when the microgrid has an option of drawing energy from the external grid (Case-4), it relies on that option to a large extent. From Table 5 it is observed that the diesel-renewable mixed microgrid (Case-3) is the most economical option when external grid connectivity is not available. However, as many rural systems are fed through local generation, it is possible that some microgrid may connect to the external grid (Case-4) due to its reliability and that would be the cheapest option. However, if there is a need for the extension of the grid then, the NPC of Case-4 can be higher than any of the other cases depending on the connectivity distance of the microgrid. This will be discussed in Section 5.3.6. It is also noted that the levelized cost of energy is significantly high in Case-1. Although in the renewable-based microgrid (Case-2) the levelized cost is reduced somewhat, to 0.639 $/kWh, it is higher than the diesel-renewable mixed microgrid (Case-3) because of the significantly large capital cost component in the former, as shown in Figs. 7 and 8. It is seen that the largest cost components in Case-1 are those of replacement, operation & maintenance and fuel costs

Table 4
Optimal microgrid plan configuration for various cases.

Component	Case-1	Case-2	Case-3	Case-4
Diesel, kW	6375	0	4250	0
Solar PV, kW	0	500	0	0
Wind, kW	0	5000	1000	0
Converter, kW	0	1000	500	0
Battery, numbers	0	20,000	10,000	0
Micro-hydro, kW	0	92	92	92
External grid, kW	0	0	0	1200

Table 5
Comparison of cost components for various cases.

Items	Case-1	Case-2	Case-3	Case-4
Net present cost, M$	21.044	14.917	6.486	1.661
Levelized cost of energy, $/kWh	0.902	0.639	0.278	0.071
Operating cost, M$/year	1.646	0.398	0.347	0.130

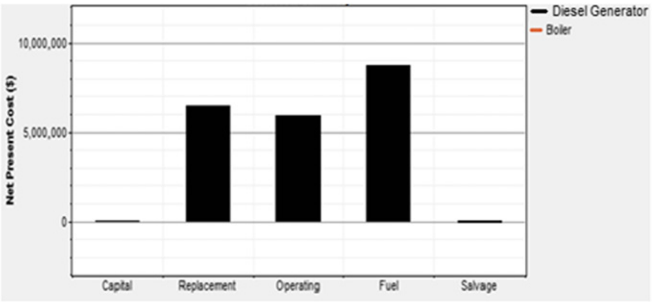

Fig. 7. Cost components for Case-1 microgrid.

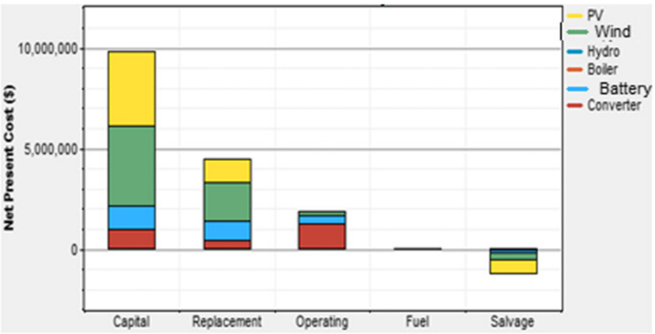

Fig. 8. Cost components for Case-2 microgrid.

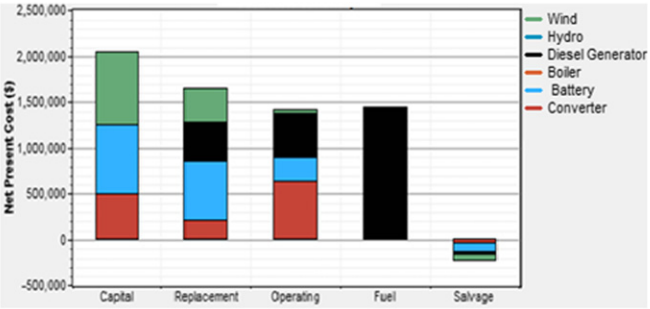

Fig. 9. Cost components for Case-3 microgrid.

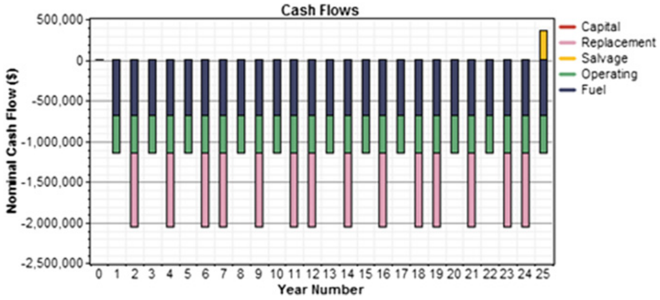

Fig. 11. Cash flow in Case-1 microgrid.

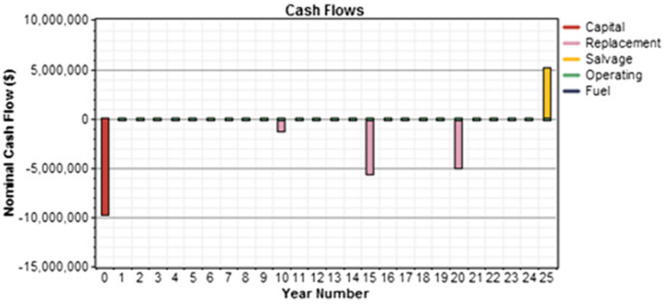

Fig. 12. Cash flow in Case-2 microgrid.

while the capital cost is zero because the system was assumed to be in place, already. The largest cost components in Case-2 are capital and replacement costs while it is noted that the operation and fuel costs are very low. In Case-3 capital, replacement, operation & maintenance and fuel costs components are equally significant as shown in Fig. 10, because of the mix of diesel with renewable sources, but they are much lower than the previous cases. In Case-4 as present in Fig. 9, the only cost component is the operation & maintenance cost which is essentially the cost of purchasing power from the grid.

Figs. 11–13 presents the annual cash flows for the all cases, respectively. It is seen that in Case-1, the diesel generators incur a replacement cost every two years because of their operating life of 5000 h. Additionally, the system incurs a regular stream of cost of fuel and operation & maintenance. On the other hand, the renewable microgrid in Case-2 only incurs an initial investment cost while the replacement cost is sporadically distributed over its lifetime. In Case-3, the cash flow pattern is similar to Case-2, with an additional regular stream accounting for operation & maintenance cost arising because of the presence of diesel generator.

5.1.2. Optimal production profiles in various microgrid configurations

Comparisons of electrical energy production and consumption for various microgrid configurations are conducted and presented in Table 6 and Figs. 14–17. As shown in Table 6, in the renewable

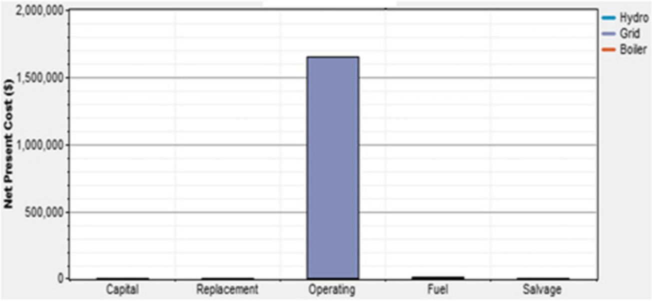

Fig. 10. Cost components for Case-4 microgrid.

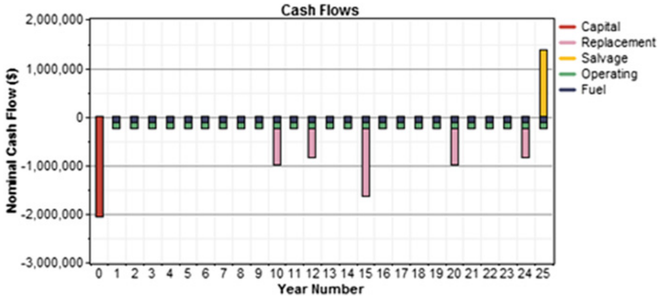

Fig. 13. Cash flow in Case-3 microgrid.

Table 6
Case-wise comparison of production and consumption.

Component	Case-1	Case-2	Case-3	Case-4
		Production, MWh/yr		
Diesel generator	4101.52 (100%)	0	1107.04 (46%)	0
Solar PV	0	633.5 (9%)	0	0
Wind	0	5962.4 (89%)	1192.48 (49%)	0
Micro-hydro	0	115 (2%)	115 (5%)	115 (6%)
External grid	0	0	0	1710.25 (94%)
Renewable energy contribution	0%	100%	53.8%	6.25%
Total	4101.52	6710.84	2414.51	1825.25
		Consumption, MWh/yr		
Electrical load energy served	1825	1824.87	1825	1825
Thermal load energy served	182.5	182.5	182.5	182.5
Excess energy to dump load	2094.02	4703.34	407.01	−182.25
Unmet energy	0	0.128	0	0

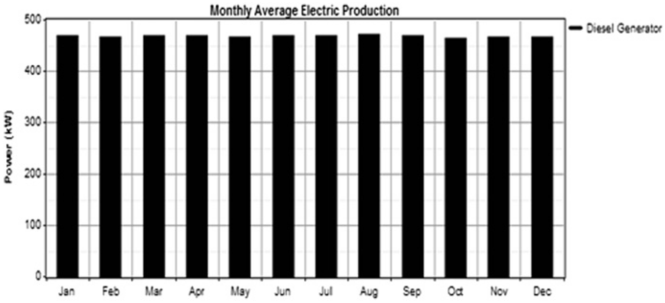

Fig. 14. Power production in Case-1 Microgrid.

microgrid based (Case-2), the total energy produced is much higher than other cases, but still there is small unmet load, while the microgrid has to dump a substantial portion of the generation energy. This is because, renewable sources are intermittent and non-dispatchable and the microgrid being fully reliant on these sources in Case-2, is exposed to these risks. It is observed that although there is enough capacity, this microgrid is not able serve the peak load at a few instances and thus the presence of energy, while it has to dump energy at some hours when the load is less. In Case-3 the excess energy is significantly reduced as compared to Case-2, because of the diesel and renewable energy mix, which results in a much lower microgrid capacity and better utilization of the generation. In Case-4 the excess energy is negative which means that the microgrid has to supply the thermal load from boilers because this microgrid essentially relies on external grid for serving its electrical load.

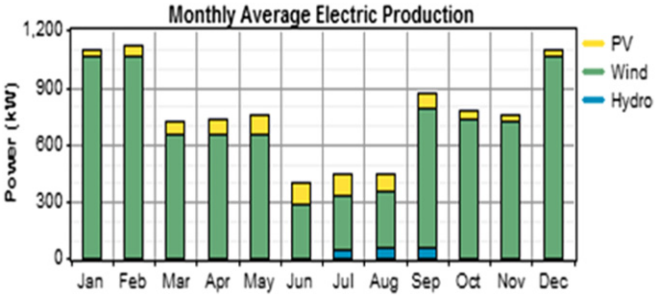

Fig. 15. Power production in Case-2 Microgrid.

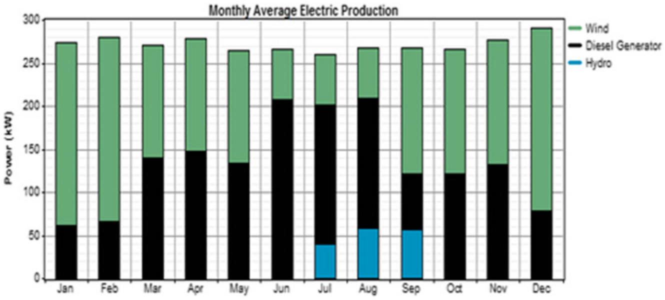

Fig. 16. Power production in Case-3 Microgrid.

5.1.3. *Comparison of environmental emissions from various microgrid configurations*

As mentioned before, one of the main objectives of this work is to reduce emissions by using green energy sources. The results presented in Table 7 shown that the renewable microgrid in Case-2 significantly reduces the total system emissions as compared to all others cases. However, although Case-3 emits more than the renewable microgrid, it is still quite environmentally friendly when compared to the diesel microgrid.

5.2. *Sensitivity analysis*

5.2.1. *Effect of unmet energy*

The effect of a capacity shortage on the microgrid is examined by allowing a small fraction of the annual load to remain unmet and determining the corresponding optimal microgrid plan, for Case-3. Two scenarios are formulated, one in which the maximum allowable unmet energy in the microgrid is 5% of the load, and the second, which has a maximum allowable unmet energy of 10%. Simulations are carried out using HOMER simulation to determine if the optimal microgrid plan of Case-3, which comprises a mix of renewable energy and diesel, is affected by the allowable margins of unmet energy. The optimal microgrid plans presented in Table 8 shows that there is a substantial change when the allowable margin of unmet energy is 5%. The diesel and wind generation capacity is significantly reduced in the later case. However, when the allowable unmet energy limit is farther relaxed to 10%, there is no further change in microgrid plan.

The variation in NPC and other cost components are presented in Table 9. It is observed that the NPC and the levelized cost of energy reduces somewhat, when allowable unmet

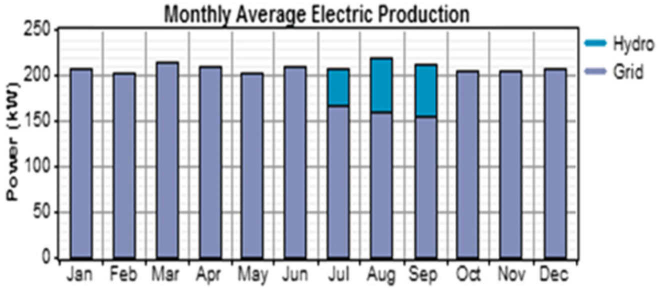

Fig. 17. Power production in Case-4 Microgrid.

Table 7
Case-wise comparison of emission.

	Emissions, ton/yr			
Pollutant	Case-1	Case-2	Case-3	Case-4
Carbon dioxide	6004.76	3.67	1078.4	1086.18
Carbon monoxide	14.82	0	2.649	0
Unburned hydrocarbons	1.64	0	0.293	0
Particulate matter	1.12	0	0.2	0
Sulfur dioxide	12.06	0.008	2.17	4.7
Nitrogen oxides	132.23	0	23.64	2.29

Table 8
Comparison of Case-3 optimal plan variation with unmet energy.

Component	Case-3 (No unmet energy)	Maximum allowable unmet energy = 5%	Maximum allowable unmet energy = 10%
Diesel, kW	4250	2125	2125
Solar PV, kW	0	0	0
Wind, kW	1000	500	500
Converter, kW	500	100	100
Battery, numbers	10,000	1000	1000
Micro-hydro, kW	92	92	92
External grid, kW	0	0	0

Table 9
Comparison of Case-3 cost components variation with unmet energy.

Items	Case-3 (No unmet energy)	Maximum allowable unmet energy = 5%	Maximum allowable unmet energy = 10%
Net present cost, M$	6.486	5.476	5.476
Levelized cost of energy, $/kWh	0.278	0.239	0.239
Operating cost, M$/year	0.347	0.384	0.384

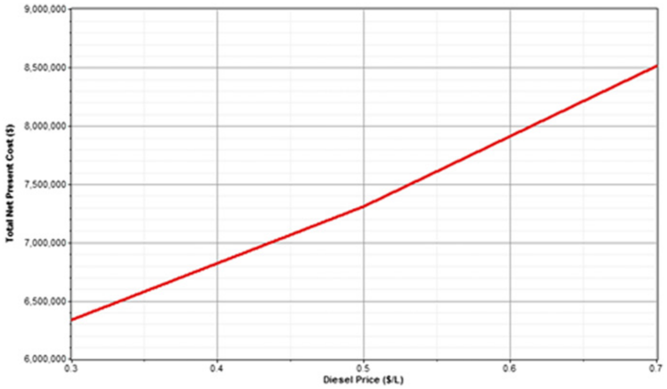

Fig. 18. Total net present cost vs. diesel price.

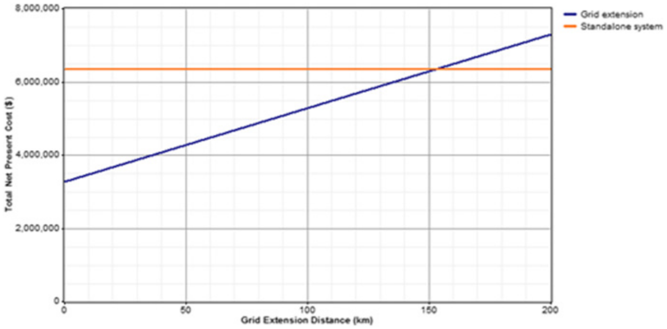

Fig. 19. Variation of NPC with grid connectivity distance for Case-4 microgrid.

energy is 5% but does not change for the 10% unmet scenario. However, the operation cost increases slightly in the presence of unmet energy because of increased utilization of diesel generation, as seen in Table 10. It is also to be noted that the actual unmet energy in the system is much lower than the allowable limit of 5% and 10% respectively, in the two cases. The microgrid indeed seeks to meet the demand optimally from its available resources as far as possible even when the unmet energy margin is relaxed.

Table 10
Comparison of Case-3 production and consumption variation with unmet energy.

Component	Case-3 (No unmet energy)	Maximum allowable unmet energy = 5%	Maximum allowable unmet energy = 10%
	Production, MWh/yr		
Diesel generator	1107.04 (46%)	1410.69 (66%)	1410.69 (66%)
Solar PV	0		
Wind	1192.48 (49%)	596.24 (28%)	596.24 (28%)
Micro-hydro	115 (5%)	115 (5%)	115 (5%)
External Grid	0	0	0
Renewable energy contribution	53.8%	33%	33%
Total	2414.51	2122	2122
	Consumption, MWh/yr		
Electrical load energy served	1825	1792	1792
Thermal load energy served	182.5	182.5	182.5
Excess energy to dump load	407.01	147.5	147.5
Unmet energy	0	32.731	32.731

5.2.2. *Effect of diesel price*

Fig. 18 shows that increase in diesel price has a significant effect on the NPC. From a base price of 0.3 $/L when the NPC is 6.48 million dollars, the NPC increases almost linearly as a function of the diesel price. At a price of 0.6 $/L, the NPC increases to 7.8 million dollars, which is a 20% increase in NPC for a 100% increase in diesel price. However, it may be noted that increase in diesel price can significantly reduce the emissions by altering the selecting of energy supply options and shifting away from diesel to renewable energy generation. Increasing the diesel price to significantly high levels may also result in a reduction in NPC.

5.2.3. *Effect of distance from grid and the optimal break-even distance*

In this analysis, the distance of the proposed microgrid is taken into consideration and the optimal plan of Case-4 is determined assuming that the microgrid can draw power from the external grid. Fig. 19 shows that the NPC of the microgrid is significantly less when it is very close to the external grid point of connection (say, 0 km). As the grid connectivity distance increases, the NPC increases, but remains lower than the one without external grid option (Case-3) for up to 153 kms. Beyond that, it is no longer economical for Case-4 microgrid to connect to the external grid.

6. Concluding remarks

This paper presents the optimal design and comparative studies for a diesel-only, a fully renewable-based, a diesel-renewable mixed, and an external grid-connected microgrid configuration. Various renewable energy options such as solar photovoltaic (PV), wind, micro-hydro and batteries are considered as possible options in the microgrid supply plan. Studies are carried out using the HOMER software which provides a very efficient tool for case studies and policy analysis.

Analysis reveal that the diesel-renewable mixed microgrid has the lowest net present cost (NPC) and a fairly small carbon footprint, when compared to a stand-alone diesel-based microgrid. Although a fully renewable-based microgrid, which has no carbon footprint, is the most preferred, the net present cost (NPC) is higher.

Analysis is also carried out to determine the break-even grid extension distance from the microgrid location. It is observed that when the microgrid is connected to the external grid (Case-4), it is the most economically favorable option because of the fact that there is no capital cost involved, and its operation and maintenance costs are much less compared to the diesel-based microgrid. In addition, the most environmentally friendly microgrid is the renewable energy microgrid (Case-2), and it results in significant savings in system emissions.

It is to be noted that there is still much work to be done in terms of renewable energy and mixed system development, because of their high initial capital and replacement costs. For example, the governmental feed-in tariffs will play a significant role in the renewable energy system cost. This work also demonstrates that allowing a small amount of annual load to be left unmet makes the microgrid (Case-3) more cost-effective. Also, the break-even distance presented in this work shows that for isolated microgrids, far away from the external grid connectivity point, the mixed microgrid (Case-3), is the most economic optimal choice. Finally, HOMER was found to be a very helpful tool for the microgrid planning and dispatching.

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