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Optimal Design and Planning of Hybrid Microgrid

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***Abstract*— During recent years, renewable energy resources are gradually recognized as great option in supply side planning of microgrids. This paper focuses on the optimal design, planning, operation, and sizing of hybrid renewable energy based microgrid with the goal of minimizing the lifecycle cost, while considering environmental emission. This paper determine the feasible configuration and component for a microgrid to perform economic and environmental analysis. First, the load profile (such as for lighting, television, electric medical equipment, electric equipment for mosque, and etc.) consumption of the rural village in 35^0.59$'$ N, 47^0.5$'$ in Kurdistan Province of Iran with considering agricultural electricity consumption (electric water pump) is estimated. Then, for supplying the estimated load, four different case studies including, diesel-only, an entirely renewable energy-based, a mixed diesel-renewable , and a grid connected microgrid configuration are designed with the aim of comparing and investigating of their economic, operational performance and environmental emission. Two sensitivity analyses are carried out to find the effects of variation in the inputs and component cost of microgrids; including, change in diesel price, maximum allowable 5% and 10 % unmet energy. For simulation purposes the well-known energy modeling software for hybrid renewable energy systems, HOMER, is used.**

Keywords-component; Microgrid; Environmental emission; Renewable energy; HOMER; Demand peak

I. Introduction

In recent years, with the constant increasing of the oil price and the costs of transmission line expansion, combined with the desire to reduce carbon dioxide emissions, renewable energy sources have become an important alternative as a power supplier especially in rural systems. It is shown that the cost of provided energy from conventional generators are less than that from renewable energy sources, but a mixed version of renewable and conventional supplier can reduce the cost of energy [1] .

With the frantic pace of growth in demand-side energy, more and more generation-side energy resources would be needed to meet this demand, which is resulted in an exponential increase in environmental pollution and global warming. On the other hand, in recent years, renewable energy which is clean and endless sources of energy, have been catching the attention of energy developers. Due to the high cost of transmission lines and higher transmission losses for remote rural isolated power systems, renewable energy sources are being known as cost effective generation sources. It is shown for a rural isolated microgrid, a combination of two or more renewable energy sources such as, wind, solar system with diesel and hydro together gives a stable energy supply in comparison with renewable energy based-only sources [17, 18']. Several researches have been carried out to investigate the optimal hybrid renewable system for isolated systems as is mentioned below.

Genetic algorithm technique is applied in [2] to find the optimal number of installed photovoltaic (PV) systems, diesel generator, and battery sets. In [3], it has been found out that a wind/PV/diesel hybrid system which were implemented in Maldives provide outstanding opportunity to demonstrate high penetration of renewable energy sources. In [4], a feasibility analysis, considering stand-alone renewable energy technology systems for remote areas in Senegal, shows that the electricity cost with utilizing renewable energy technology will be lower than that of obtain form grid extensions. Furthermore, the renewable energy technologies have friendly impact on the environment.

Review of simulation and optimization techniques for finding optimal configuration of PV generator, wind turbine and diesel generator, to generate electricity, has been done in [5]. In [6], the authors developed the optimum sizing methodology to determine the optimal dimensions of hybrid energy supply system, while minimizing the capital cost. It has been shown that the most appealing energy supply option for the support of remote telecommunication stations is proposed hybrid power system consisting of PV, diesel, inverter and batteries. In [7], a Mixed Integrator Linear Programming (MILP) model is proposed for optimal planning of renewable energy system for an area in Malaysia to meet a specific CO_2 emission reduction target. A mathematical model and optimization algorithm as well as use the Hybrid Optimization Model for Electric Renewable (HOMER) software is used to determine optimal microgrid configuration and their optimal generation in mixed mode [8, 9].

The authors in [10] investigate the ways to minimize the fuel usage and therefore, minimize the CO_2 emission while trying to maintain a high level of reliability and power quality of the microgrid. This goal is achieved by maximizing the utilization of renewable energy resources, dispatching and scheduling the conventional generators at their optimal efficiency operating points, by means of storing extra energy in storage systems, with the goal of reducing the dependency on the utility grid. A methodology for design and economic feasibility evaluation of the microgrid, with the renewable energy resources, are proposed in [11]. The economic operation of combined heat and power (CHP) system comprising of fuel cells, wind power, batteries and heat recovery boiler is discussed in [12] utilizing nonlinear optimization method. In addition, 24 hours forecasting for wind speed, solar irradiation, heat and electricity demand is investigated as well. The optimal operation of microgrid including PV, wind power, and battery discussed in [13] with using heuristic algorithm and linear model. Then, the results showed that using batteries can reduce the microgrid operating cost.

In [16], [14], a comparative analysis among diesel, PV-diesel, and hydro-diesel is presented to investigate the field performance of different off-grid generation technologies which are applied to the electrification of rural village.

Several factors will be required to be defined for planning of the rural microgrid which is comprised of renewable energy sources such as: choosing the proper type of renewable energy resources among different power resources, determination of the number and the capacity of the sources which will be used, consideration the total system cost, determining the distance from the nearest grid connecting point, providing the option of connecting to the main grid, consideration of the extra energy which is obtained from the microgrid or the utility grid, and finally unmet loads. In this paper, a few numbers of aforementioned factors, as well as their effect on the proposed system are examined.

The main motivation of this paper can be outlined as follows:

- Obtaining optimal planning and design of renewable energy based microgrid with different renewable energy components and with realistic inputs on their physical, economic and operation characteristic.
- Comparing the overall benefits from the obtained optimal designed microgrids with existing microgrid configuration.
- Performing and studying the sensitivity analysis for the designed microgrid.

The rest of paper is organized as follows: in Section II, the load profile of the specific rural village in Kurdistan province in Iran will be estimated and system input data are introduced. The brief description of the considered microgrid is presented in Section III. Section IV gives the analysis and discussion of the results which is obtained from HOMER software. Section V, presents the summary and conclusion of this paper.

II. Load Estimation of the Rural Microgrid

A. Load Profile Estimation

The estimation of the load is associated to the village electricity consumption which the microgrid will be designed for and is comprised of:

1) 200 houses (considering 5 person as an average for each house)

The electricity equipment which each house uses is considered as follows:

- Refrigerator (with 300 watts/hour)
- Four 100 watts/hour electric bulbs
- Television (with 400 watts/hour)
- Water cooler (with the 500 watts/hour for hot seasons)
- Vacuum Cleaner (1000 watts/hour)

2) Boarding Clinic

The village has boarding clinic which has:

- Seven 100 watts/hour electric bulbs
- Refrigerator (with 300 watts/hour consumption)
- Television (with 300 watts/hour consumption)
- Water cooler (with 700 watts/hour consumption)
- Medical electric equipment (with 1000 watts/hour consumption)

3) School

The village has a double-shift school with four classrooms which is included in:

- Five electric bulbs (with 100 watts/hour consumption for each one)
- Water cooler (with 700 watts/hour consumption)
- Television (with 300 watts/hour consumption)

4) Mosque

The village mosque has electric amplifier and speakers which will be used for call for prayer in a specific time. The mosque electric equipment is as follows:

- Ten electric bulbs (with 100 watts/hour consumption for each one)
- Water cooler (with 700 watts/hour consumption)
- 400 watts/hour electricity consumption for mosque electrical amplifiers and its speakersIt is noteworthy that the house's water cooling in the

village are considered to be turned on from the June to the end of the September from around 10 a.m. to 16 p.m. and this issue is considered in load estimation procedure.

In Table 1, three different statuses for hourly load profile of the entire village and during an ordinary day in July are shown.

Table 1. Three different statuses for estimated load profile of the village for each hour

Demand Status	Hourly Electricity Consumption of the Village (Lower to Upper)
Low Peak	2.1 to 3.4 Kw
Medium Peak	4.2 to 5.6 Kw
High Peak	5.9 to 7.7 kw

5) Agricultural Electricity Consumption

For agricultural purposes, farmers would be needed to extract water from the water wells, by means of electricity water pumps. The amount of harvested water from water wells are strongly depended on several factors such as village geography, the village climate, and rated power of water pumps. Based on the investigation which was carried out about village climate, farmers use a wide range of electric water pumps with the quantity from 0 to 30, and with variable power from 5 Kw to 50 Kw (5, 10, 15, 30, and 50 Kw). The under consideration village uses 12 water wells with different rated of power for each electric pump which are shown in Table 2:

Table 2. The rated power of utilized electric water pumps for agricultural purposes.

Rated Power of each pump (Kw)	5	15	30
Quantities of utilized electric water pumps	6	4	2

The electricity tariffs for agricultural consumption are considered as below [17]:

- 4/3500 dollar for low peak demand
- 8/3500 dollar for medium peak demand
- 16/3500 dollar for high peak demand

Therefore, farmers have to turn their pumps on in a specific hours during day and night (low and medium peak hours). The peak of agricultural activities is mostly limited in May to October. Based on the carried out investigation, the number of hours in each month which the pumps are utilized are as follows:

- For May and October, the pumps will be turned on for an hour in the morning (from 4 a.m. to 5 a.m.) and for an hour in the afternoon (from 15 p.m. to 16 p.m.)
- For Jun and September for two hours in the morning (from 4a.m. to 6 a.m.) and two hours in the afternoon (befromtween15p.m. to 17 p.m.)
- For July to September for three hours in the morning (from 4 a.m. to 7 a.m.) and three hours (from 15 p.m. to 18 p.m.)

In Figs 1 and 2, the estimated daily load profile are illustrate for July (highest demand peak) and April (lowest demand peak), respectively.

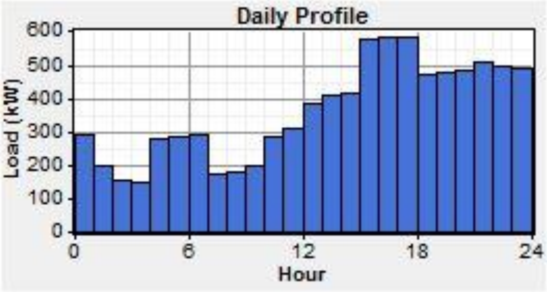

Fig.1 .Hourly electrical load profile for **July** month for microgrid.

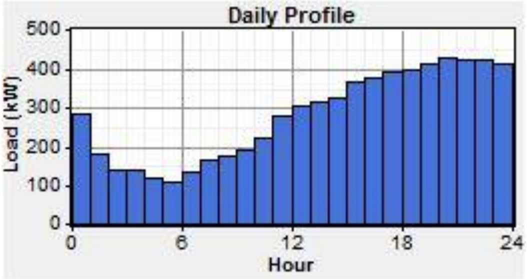

Fig.2 .Hourly electrical load profile for **April** month for microgrid.

The annual load profile of the village is shown in Fig. 3. Due to the higher rate of electricity consumption of the village during July and August (higher rate of agricultural activities and electric water pumps for agricultural purposes and also higher rate of temperature in this area and consequently higher rate of water cooling) the biggest value for the annual load profile is allocated to these two months.

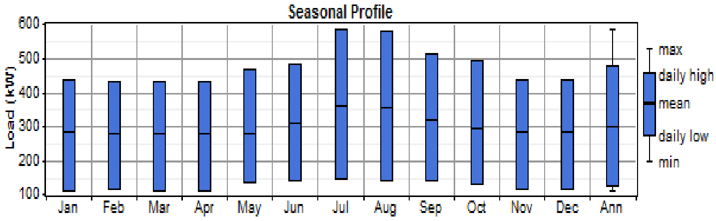

Fig. 3. Annual average load profile for 12 months.

According to the Fig. 1, the peak demand hours are not the same for all of the year's months. For example, peak demand hours in hot seasons is limited into 21 p.m. to 24 p.m. and on the other hand, in the cold seasons the peak demand is from 20 p.m. to 24 p.m. It is worth noting that the value of the load factor (LF) is obtained around 0.515 for our under consideration load profile which is close to the actual load factor of Iran. Although, the LF' values vary typically from 0.7 to 0.85 for developed countries.

demand were 6681Kw and 420 Kw for April, respectively.

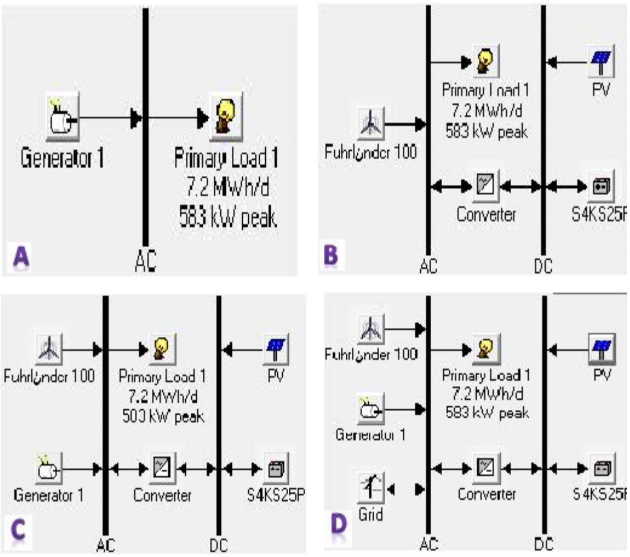

Fig. 4. Comparison of various optimal microgrid configurations A) Microgrid 1. B) Microgrid 2. C) Microgrid 3 and D) Microgrid 4

III. Under Consideration Microgrid

The available energy supply option in the hybrid microgrid system (the designed and under consideration microgrid in Kurdistan province) are wind turbines, solar PV array, battery bank, diesel generator, dump load, and bidirectional DC/AC converter (Fig. 4). As shown in Table 3, four microgrids with different components are designed as follows:

Table 3: Summary of the designed microgrids

Designed microgrids	Description of the Microgrid
Microgrid 1	Diesel generator-based only (Base Case)
Microgrid 2	Renewable energy-based only
Microgrid 3	Renewable energy + diesel generator
Microgrid 4	Microgrid 3 connected to the external grid

The characteristic and cost of the system components are presented in the following subsection.

A. Assumptions and model inputs

1) Electrical load

As mentioned in pervious section, the load profile of the proposed rural community is shown in Figs1-3. The microgrid load is consisted of electrical load of the village and their agricultural consumption. The maximum consumed energy during a day and higher peak demand were 8446 Kw and 583 Kw, respectively, for July month and the lowest energy consumption and lowest peak demand were 6681Kw and 420 Kw for April, respectively.

2) Wind resource

The wind speed data are obtained from [15]. Based on the wind speed profile, the annual average wind for this area is 7.715 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 30 m.

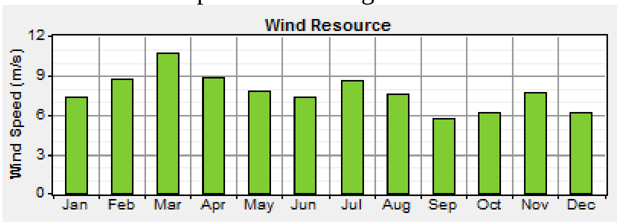

Fig. 5. Wind speed profile for the considered rural area.

3) Solar recource

The solar radiation data for the considered area ($35^0.59'$ N, $47^0.5'$) is obtained from the NASA Surface Meteorology and Solar Energy website [15]. The annual average sun irradiation for the considered microgrid is 5.231 kwh/m^2/day.

The capital and replacement costs of photovoltaic (PV) arrays including; shipping, tariffs, installation and dealer mark-ups is considered.

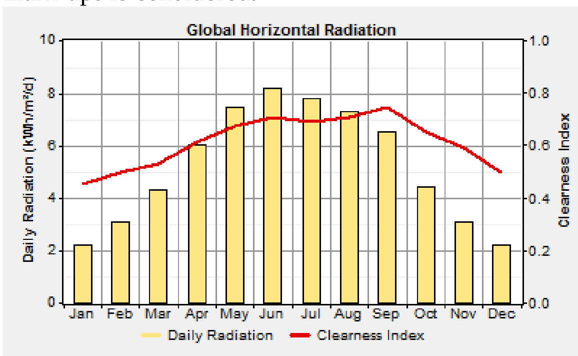

Fig. 6. Sun irradiation profile for the considered rural area.

4) Diesel price

The study includes a sensitivity analysis on the price of diesel, which can be varied considerably based on the current market, the region, and transportation costs. The optimal planning of the microgrid with the diesel price of 0.143 $/L (base price) and 0.286 $/L will be evaluated. For the diesel, emission density of 740 kg/m^3, carbon content of 86% and sulfur content of 0.33% is considered.

5) System economics

As shown in Fig. 7, three different tariffs are considered for the electricity purchase rates from the external grid. The considered rates are based on current exchange dollar price which is 35000 units that of Iran currency (Rial). The purchasing price for low demand peak (green color), the medium demand peak (yellow color), and the high demand peak are considered $0.006, $0.012, and $0.024, respectively. The electricity sell rate from microgrid to the main grid is considered constant and is about $0.06 during the 24 hours.

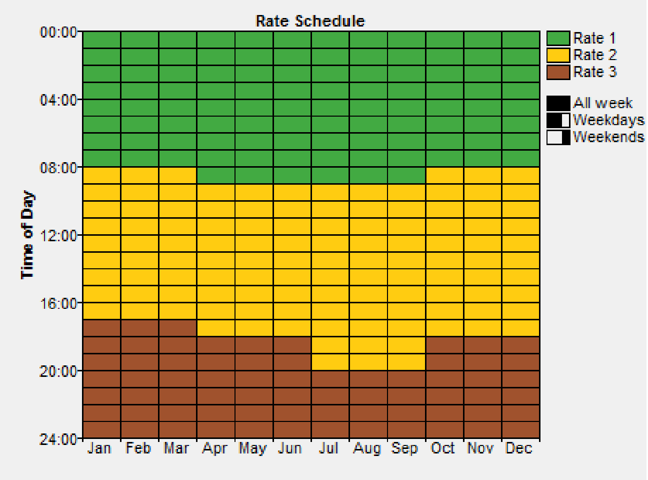

Fig. 7. Rate scheduling for purchasing electricity from the external grid during the 24 hours for 12 months.

Input data and option costs, sizing and other parameters are presented in Table 4.

Table 4. Input data and option costs for the under consideration microgrid.

Options	Capital cost	Replacement cost	Q & M
Wind	$40000	$35000	$500/h
Solar	$ 5500	$5500	$50/yr
Battery	$1500/Battery	$1500/Battery	$50/Battery/yr
Converter	$ 1200	$ 1200	&150/yr
Grid Extension	&20000/Km	&20000/Km	&15/yr
Diesel Generator	$400/Kw	$300/Kw	$0.05/h

6) Power Converter

HOMER software considers a converter as a bidirectional AC/DC converter to exchange power from the DC bus to AC and vice-versa. For 1Kw system the replacement and installation costs are taken as $1200. A model lifetime and the efficiency of the considered converters are 15 years and 85 percent.

IV. Results and Discussion

HOMER is a simulation tool 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 operation costs over its lifespan, is modeled using HOMER [18]. In the area of the simulation, HOMER determines technical feasibility and lifecycle costs of a microgrid for each hour of the year. Furthermore, the microgrid configuration and the operation strategy of the supply components, work in a given setting over a period of time. It's noteworthy that the optimization and sensitivity analysis of HOMER depends on the simulation capability. In the optimization feasibility section, HOMER demonstrate the feasible system with their configuration under the search space defined by the user, stored by the minimum cost microgrid depending on the total net present cost (NPC) [18] Another capability of the HOMER software is the sensitivity analysis. The main objective of sensitivity analysis is that if the user isn't sure which is the best value of a particular variable, then the user can enter different values and the sensitivity analysis will show how results behave dependent on these variables.

In this section, four different microgrids (with different components) are designed (see Table 3) to determine the most favorable microgrid for planning. In Table 3, Microgrid 1 is assumed to be already in the place and is being supplied by an isolated network which is fed by diesel generator. On one hand this type of microgrids (which is located in remote area) are strongly dependent on the imported fuel supply and fuel transportation. On the other hand the diesel generators are highly emission intensive. In Microgrid 2, we considered that the microgrid components are entirely based on the renewable energy sources. Microgrid 3 is a mixed configuration which is comprised of both of Microgrid 1 and 2, while, the last microgrid in Table 3, is considered as the Microgrid 3 but with the additional option to connect to the main grid to get or draw energy from/to the external grid.

A. Comparison of designed Microgrids

1) Impacts of optimal plan configurations and cost components on the Net Presence Cost

The optimal microgrid design for Microgrids 1 to 4, are obtained from HOMER simulation, using the parameters which were described in section III. The optimal configuration of the obtained microgrids from Microgrids 1 to 4 is shown is the Fig. 4(a)-(d). The optimal sizes of the microgrid components for different cases are shown in Table 5.

The main motivation of this paper is to find the least-cost microgrid plan for different microgrid design while taking into account the environmental effects of the each plan. From the obtained optimal microgrid (see Fig. 4 and Table 5), it is seen that Microgrid 1 is dependent entirely on the diesel capacity and selects 621 Kw as its capacity to meet its demand. Microgrid 2 is completely relies on its batteries, converters, and wind turbines, and PVs, while the diesel generator in Microgrid 3, reduced its generation from 621 Kw to 400 Kw, because the electrical load receives its demand from other renewable resources such as, wind turbines, batteries, converters and PVs to meet the needed energy. When microgrid has an additional option to get or draw electricity from/to external grid (Microgrid 4), the microgrid relies on this option to a large extent, because, the rates (three tariffs) of electricity purchase from the grid is really low in compared with other microgrid component costs.

As shown is Table 5, Microgrid 4, is the most economical option due to the lowest value ($1607185) of its net present cost (NPC). This value shows that the microgrid gets profit even though it purchases electricity from the external grid.

Table 5. Optimal microgrid plan configuration for different cases

Components Microgrid / Cases	Diesel Generator (Kw)	Converter (Kw)	Number of Batteries	Number of Turbines	Power from Grid (Kw)	PV(Kw)	NPC ($)	Environmental emission (kg/yr)
Microgrid 1	621	-	-	-	-	-	7742987	2586610
Microgrid 2	-	550	1975	45	-	-	10357325	0
Microgrid 3	400	165	130	16	-	-	3758563	699423
Microgrid 4	-	-	-	30	525	-	1607185	2703750

Based on aforementioned reasons, it's obvious that drawing electricity from the main grid is the cheapest option which is provided for Microgrid 4. The second order is allocated to Microgrid 3 which is comprised of renewable energies and diesel generator. Therefore, for microgrid which has not the capability to connect to the external grid, the mixed microgrid could be a most beneficial among other configuration. It must be mentioned that the grid connecting option will not lead to the most beneficial option for every microgrids. The connectivity distance of the microgrid can have a key role in NPC of the microgrid. This issue will not be discussed in this paper. The third order in the NPC, is allocated to Microgrid 1, because, the price of fuel cost and also diesel generator cost is very low in compared to the component costs of the Microgrid 2.

2) Camparison of the amount of environmental emission for various microgrid configuration

Similar to the pervious subsection, the results of optimal size of the microgrids components for different cases are shown in Table 5. But, in this subsection we consider the impacts of obtained optimal size from HOMER on the amount of environmental emission for Microgrids 1 to 4. As it is shown in Table 5, due to the utilization of renewable energy resources (with zero environmental emission) the first order is allocated to Microgrid 2. The second, third, and forth order from environmental point of view belong to Microgrid 3 (with 699423 Kg/year environmental pollution), Microgrid 1 (with 2586610 Kg/year environmental pollution), and Microgrid 4 (with 2703750 Kg/year environmental pollution), respectively. Microgrid 3 uses mix renewable energy and diesel generator, therefore the amount of pollutant is derived from diesel generator-only. In Microgrid 4, in addition to wind power source, the rest of power is mainly provided from grid. Due to the higher amount of environmental pollutant of the external grid rather than diesel generator (for example in Microgrid 1) the forth order is allocated to Microgrid 4.

B. Sensitivity Analysis

As mentioned previously, the main objective of sensitivity analysis is to finding optimal value from the possible results when the user changes the variables and does not know about its possible effects on the results. The effects of unmet energy, and change in diesel price are examined on the Microgrid 3.

1) Effect of unmet energy

The effect of capacity shortage on the microgrid is examined by allowing a relatively small fraction of the annual load to remain unmet and determining the corresponding effects on the NPC and environmental emission of the optimal microgrid plan, for Microgrid 3. Two scenarios are constructed. The first one is that the maximum allowable unmet energy in the Microgrid 3 is 5% of the entire load, and the second one which has a maximum allowable unmet energy of 10%. The motivation behind the two mentioned scenario is trying to determine the effects of various amount of unmet energy on the optimal microgrid plan of Microgrid 3, which is consisted of a mix of renewable energy and diesel generator. The optimal microgrid plan presented in Table 6 show that there is an outstanding change in NPC of the microgrid when the allowable margin of unmet energy is 5%; even though the lowest NPC is obtained for maximum allowable 10% unmet load. It is shown for both 5% and 10% allowable unmet energy; the microgrid does not use its converters and batteries. On the other hand, for the both scenarios, microgrid has reduced its dependency on diesel generator and increase the quantity of wind turbines to meet the energy demand. In the environmental point of view, the maximum allowable 10 % for unmet energy has led to lowest amount of pollution.

Table. 6. Comparison of Microgrid 3 optimal plan with variation in Maximum allowance of unmet energy

Components Microgrid / Scenarios	Diesel Generator (Kw)	Converter (Kw)	Number of Batteries	Number of Turbines	Power from Grid (Kw)	PV(Kw)	NPC	Environmental Emission (kg/yr)
No Unmet Energy	400	165	130	16	-	-	3758563	679423
Maximum Allowable 5% Unmet Energy	300	-	-	24	-	-	3152231	593498
Maximum allowable 10% Unmet Energy	-	-	-	19	-	-	2647840	564879

Furthermore, the effects of maximum allowable 5% and 10 % unmet load on environmental emission are shown in Table 6. The amount of environmental emission is 679423 kg/yr for no unmet energy which is reduced to 593498 kg/yr and 564879 kg/yr for maximum allowable 5% and 10 % unmet demand, respectively.

2) Effect of diesel price

Table 7 shows that increase in diesel price has a significant effect on the NPC. When the diesel price rises from the base price, 0.143 $/L, to 0.286 $/L, the NPC increases from $3758563 for the base NPC to $4380760 which is related to the 100% increase in diesel price.

It may be noted that increase in diesel price can significantly reduce emission by changing the selecting the energy supply options and shifting away from diesel to renewable energy generation. But in the considered microgrid, the diesel price is too low (in compared with other microgrid components) to affect diesel generation significantly. Therefore, the amount of reduce in emissions is not remarkable.

V. Conclution

This paper presents an optimal design by considering different microgrids with different components and Configurations such as diesel-only, a fully renewable-based, diesel- mixed with renewable energy and external grid connected microgrid configuration.

Several renewable energy options such as solar PVs, wind turbines, batteries are considered as a possible option in the final microgrid supply plan. The simulations are carried out using HOMER software which is the one of the most efficient tool for case studies. Simulation results showed that diesel-renewable mixed microgrid (Microgrid 3) has the lowest net present cost (NPC) in compared with standalone diesel generator –based microgrid (Microgrid 1). Analysis reveals that the fully renewable energy-based microgrid (Microgrid 2), which has no carbon footprint, is the most preferred in this point of view, but its NPC is still higher than Microgrid 1.

It is noteworthy that the most environmentally friendly is fully renewable energy-based (Microgrid 2) which results in remarkable saving in system emission.

This paper also illustrated, even, small fraction of annual load to be left unmet, makes the Microgrid 3 more cost-effective. This issue is more visible for 5% maximum allowance for unmet energy. Also, it is demonstrated, 100 % increase in diesel price (as sensitivity analysis) leads to lower amount of NPC and environmental emission but the amounts of reduction are not significant, because, the diesel price is too low in compared with other microgrid component costs.

Table. 7. Comparison of Microgrid 3 optimal plan with variation in diesel price

Components Microgrid / Scenarios	Diesel Generator(Kw)	Converter (Kw)	Number of Batteries	Number of Turbines	Power from Grid (Kw)	PV(Kw)	NPC	Environmental Emission (kg/yr)
No change in diesel price	400	165	130	16	-	-	3758563	679423
100% increase in diesel price	300	-	-	24	-	-	3152231	593498

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