Feasibility Study of a Hybrid Energy System for Emergency Off-grid Operating Conditions

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ABSTRACT
Taking the advantages of alternative energy sources is currently a trending concept in the field of energy management. Meanwhile, microgrids and hybrid energy systems are of great importance due to their numerous benefits for both consumers and utility. This paper presents technical feasibility study of a hybrid energy system, including renewable and non-renewable resources and energy storage system, for electrification of a Disaster Management Basement located in Tehran, Iran. To simulate the potential power blackout caused by a disaster, the proposed system is simulated and optimized in off-grid mode, using HOMER simulation software. Since the disaster occurrence is unpredictable, while the system is simulated in a whole year, the results are analyzed in two winter and summer cases. Regarding reliability of the system, a sensitivity analysis is carried out. It was found that with diesel prices up to 0.5-0.6 $/L, the only optimal power system is diesel generator. With prices more than this, wind and solar power sources should be added to the power system. As the main result of the paper, it was found that renewables can act as good backup power systems in cases of shortages in conventional energy resources to ensure high reliability of the system.

KEYWORDS: Microgrid optimization, Energy management, HOMER, Reliability, Technical feasibility, Diesel price.

1. INTRODUCTION

Today’s electric power network is based on central generation units, which provides a one-way path of power from generation to consumption. By the introduction of smart grids, several new concepts have been entered the power generation, distribution and consumption areas. One of these new concepts microgrids (MGs) and integration of distributed generation (DG) systems into them. Microgrids integrated with distributed energy resources (DER), as a turning point, have changed the future architecture of power networks. Numerous significant factors, such as fossil fuels depletion, global environmental awareness about current power generation methods, emerging new renewable energy sources (RES) and technologies and governmental laws and incentives on RES-based power generation, have accelerated the growing use of DG systems [1].

Microgrids, as an integral part of future power network, offer several advantages including higher energy efficiency and quality, facilitating higher penetration of RES, less environmental impacts and emissions, more reliability of power supply, and economic savings in energy costs [2]. Moreover, microgrids can ease the use of energy storage systems (ESS), leading to higher reliability.

Integrating RES, such as PV cells and wind turbines into conventional local power generation units, such as diesel generators, is the most important feature of a MG, which can form a hybrid energy system (HES). This can visibly enhance the robustness of the power distribution system.

The main objective of MG designing process, containing various energy sources, is optimal sizing of energy sources, as well as optimal power supply management to meet the load demands in a cost-effective way. This objective may be handled whether in a grid-connected mode or off-grid mode. Various optimization methods and algorithms can be applied to MG designing. Additionally, several simulation software packs have been developed to ease the simulation and optimization of MG and HES.

In this paper, a MG is designed and optimized for an office building in Tehran. The case study building is one of the basements of Tehran Disaster Mitigation and Management Organization (TDMMO). The MG is studied in the off-grid mode to simulate the disaster conditions which may lead to a blackout. Optimization tool selected for this paper is HOMER software.

Finally, a sensitivity analysis is conducted to assess possible uncertainties during MG performance.

2. LITERATURE REVIEW

In the optimization process of a hybrid energy system, several objective functions may be considered. These includes optimal component sizing regarding minimization of cost, emission, etc. or maximization of reliability, renewable fraction, etc. and control and energy management of the system such as operating costs control or management of energy supply, power quality and power dispatch. Meanwhile, various methods can be applied for the optimization process. Some optimizations are conducted via mathematical optimization algorithms such as genetic algorithm, particle swarm optimization, imperial competitive algorithm, etc. [3-5], while others use some related computer programs such as HOMER, System Advisor Model (SAM), Hybrid2 and RETSCREEN [6-8].

Some studies used HOMER for the optimization of hybrid energy systems [9-12]. In a research by de Christo et al. [13] design and analysis of a hybrid energy system for an Antarctic Station was carried out. Both thermal and electrical loads were considered and the best combination of the energy system was proposed. Park and Kwon [14] studied the potential solutions for establishing independent renewable power generation systems in Gadeokdo Island, one of the largest islands in South Korea. The system achieved $0.326 per kWh of Cost of Energy and 100% of renewable fraction. Rezzouk and Mellit [15] studied techno-economic feasibility of a hybrid energy system for a research unit located in north of Algeria. Kumar and Bhimasingu [16] optimized a power system for a set of residential buildings in India. Four scenarios were considered and the optimization was applied in to off-grid and grid-connected modes. Olatomiwa et al. [17] studied feasibility of powering a specific remote mobile base transceiver station (BTS) in Nigeria using solar and wind energy. Kebede [18] explored the potential of grid-connected solar PV power generation in Ethiopia. Both HOMER and RETScreen software were employed in this study and it was found that the average value of PV power plant capacity factor of the different locations considered is 19.8%. Olatomiwa et al. [19] conducted the techno-economic feasibility of utilizing hybrid photovoltaic/wind/diesel with battery storage systems to meet the load of a typical rural healthcare facility at selected locations across six geo-political regions of Nigeria. Hafez and Bhattacharya [20] carried out the optimal sizing and operation of a hybrid energy system based on renewable energies. Four different combinations of the energy system were considered and optimization was applied to meet electrical and thermal loads. Mirzaei ans Vahidi [21] presented the feasibility study and optimal design of different stand-alone and grid-connected renewable energy systems (RES) to supply power for a dairy factory in Tehran, Iran. Ghiani et al. [22] conducted optimal sizing and operation strategy of a smart MG in order to maximize the self-consumption of the energy produced by the system. Kolhe et al. [23] investigated the optimum configuration of a hybrid system that can supply electricity to a rural community in Sri Lanka, which comprises approximately 150 households with a resultant daily electricity demand of 270 kWh and a nighttime peak of 25 kW.

3. PROBLEM CONFIGURATION

Being on an area with high potentials of natural disasters, especially earthquake, Tehran, the Iranian capital city, faces major dangers and challenges. Resolving these challenges requires urgent actions. Therefore, TDMMO has founded about 120 disaster management bases in different areas of the city. When a natural disaster occurs, these bases have a critical role in ceasing the catastrophic situations and facilitating the aids to damaged areas and people.

The energy network of the city, the electricity grid included, may experience serious damages after a disaster. Therefore, the energy supply of disaster management bases should be as robust and immune as possible.

Since the renewable energy sources are local and independent of grid situation, they are of good alternatives to form an energy supply system for an important building, e.g. disaster management buildings.

HOMER optimizes hybrid energy systems while considering them working full time during their given lifetime. In the case of this paper, since the occurrence and duration of the grid outage is unpredictable, it is considered that the system is virtually working in full time mode to analyze the real time availability of the system in cases of emergency.

In normal conditions, the building load is met by the grid, while in disaster situations, the building will be excluded from the grid supply. To analyze the emergency off-grid conditions, two states are considered:

a) The emergency condition happens in mid-winter period and the grid outage lasts at least ten days (Feb. 11th to Feb. 20th).

b) The emergency condition happens in mid-summer period and the grid outage lasts at least ten days (Aug. 11th to Aug. 20th).

3.1. Case Study

In this research, one of the disaster management bases, located in Northern Tehran, is selected as the case study. The building has three floors. The relatively large rooftop area makes solar photovoltaic (PV) a reasonable option for HES. There is a flat area in the vicinity of the building, so that some small wind turbines (WT) can be erected. The demand of the building is met by the utility grid. In case of blackouts, a 12 kW diesel generator (GEN) is installed to meet certain urgent loads. The load profile of the building, on a catastrophic day, is as in the following sections. The system is modeled and optimized in HOMER and the best configurations are estimated.

3.1.1. Load Profile

On an urgent situation, only primary loads should be met and non-priority loads have to be neglected in the dispatch program. In disaster situations, extra and deferrable loads are neglected. Primary loads, which is going to be met in this situation, consists lighting loads, computers and communication sets, and some other partial necessary loads. Table 1 presents the percentage of these categories. Assuming that the building will need power for 24 hours of the day due to its critical tasks, it has been considered that the load is approximately in a constant interval with small changes in lighting loads. A day-to-day and hour-to-hour random variability of 5% is set to create random and unique load profile for each day. Fig. 1 illustrates a typical daily load profile.

Table 1. Primary loads of the building.

Load type	Percentage
Lighting	54
Computers and communication sets	36
Other loads	10

3.1.2. Solar and wind resources

Iran, locating in a region with average daily radiation of 5 kWh/m2/day, has about 2800 sunny hours per year, which turns the country to a good potential for solar energy harvesting area [24], [25]. Wind energy, whether in form of large-scale generation or local distributed generation, also is a remarkable renewable energy alternative in Iran. The case study building is located in latitude of 35.6 (North) and longitude of 51.4 (East), and therefore enjoys a good solar radiation and the wind potential is relatively high. Average annual solar radiation and wind speed is extracted from Ref. [26] and depicted in Figs. 2 and 3 respectively. It is clear from the figures that months May to August are the best time interval for RES extraction.

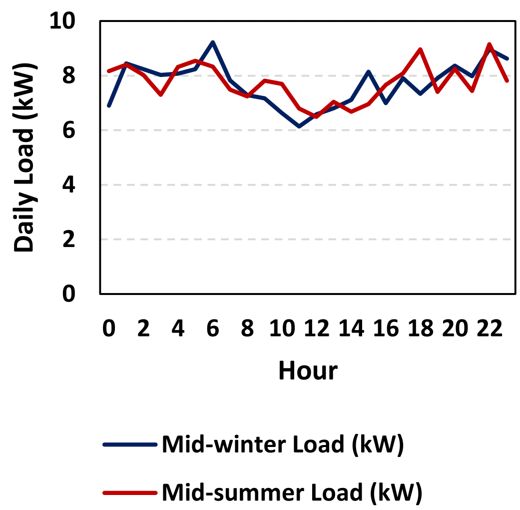

Fig. 1. An average daily load profile

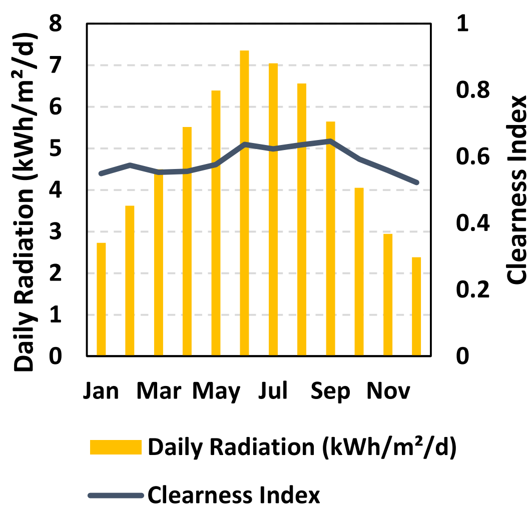

Fig. 2. Annual average solar radiation

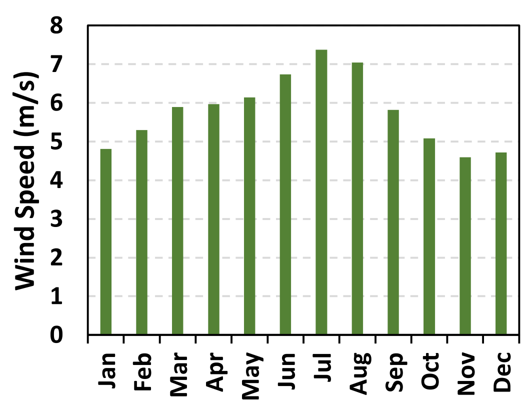

Fig. 3. Annual average wind speed at height of 50m

3.2. Microgrid Architecture and Optimization

3.2.1. Microgrid components

The proposed MG for this study is comprised of five major components including diesel generator, mini wind turbine, solar PV panels, bi-directional converter and storage system. Fig. 4 shows the configuration of the MG. Choosing the best size of each component is a critical objective to meet the demand loads at the most cost-effective way. The sizing options presented in Table 2 are considered in this study. Moreover, knowing technical features of each component is a key factor in modeling the MG.

A 12kW diesel generator is already installed in the building and therefore its capital cost is set to zero. Iran is among the rich countries in fossil fuel resources and therefore, compared to most developed resource-less countries, fossil fuel prices are low. Diesel price in Iran is about 0.1$ per liter and this is set for the diesel generator fuel price.

The wind turbine considered for modeling is a small 6 kW wind turbine with hub height of 30m. The building vicinity allows to maximum of 2 turbines to be erected. Monocrystalline 250Wp PV panels are considered and the maximum allowable size in rooftop area of the building is about 13 kW. Four sizes of battery strings, each with 8 batteries of 1 kWh capacity, are considered. A simple converter is selected and the size options are the same as PV panel. Size options and economic data of the MG components, i.e. capital costs and operating and maintenance (O&M) costs, are presented in Table 2.

Table 2. Primary loads of the building.

Component	Capital cost	O&M cost	Size options
Wind Turbine	18000 $/quantity	90 $/year	0, 1, 2 turbines
PV Panels	2500 $/kW	10 $/kW	0, 4, 8, 12 kW
Diesel Generator	0	0.02 $/kWh	0, 12 kW
Battery	350 $/quantity	10 $/year	0, 2, 4, 6, 8 strings
Converter	250 $/kW	10 $/year	0, 4, 8, 12 kW

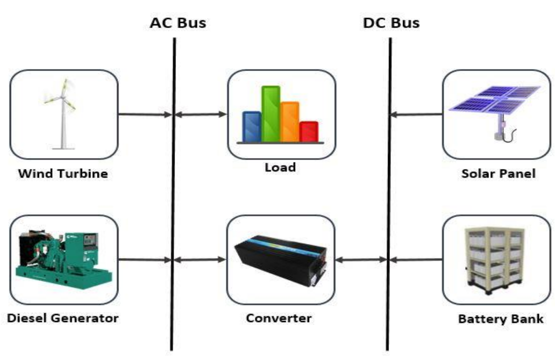

Fig. 4. The Microgrid Architecture

3.2.2. Optimization process

Economic analysis is an integral part of a MG designing and optimization process. Since a MG comprises of several components, MG designing deals with different cost functions. MGs have both renewable and non-renewable energy sources. As the cost features of these two sources are dramatically different, the economic analysis should be performed thoroughly. In other words, renewable energy sources have a high capital cost, while their operating cost is relatively low. In contrast, non-renewable sources tend to have a low capital cost and high operating cost. To cover all these various cost characteristics, Life Cycle Cost (LCC) analysis is applied [27].

Among several economic terms and concepts, HOMER uses total net present cost (NPC) of a system to provide a LCC analysis. NPC calculates all different costs and revenues of a system during its lifetime and presents a cost number in current dollar. Therefore, it provides a good sense for a detailed comparison. The objective of HOMER economic calculation is to find a system configuration with the minimum NPC and to sort different MG configurations in order of minimum to maximum NPC.

The total net present cost ($) is calculated by the following equation [27]:

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{project})} \quad (1)$$

where, $C_{ann,tot}$ is the total annualized cost ($/yr.), CRF is the capital recovery factor, i is the real interest rate (%) and finally, $R_{project}$ is the project lifetime (yr.). The total annualized cost is the sum of different costs of a system component and is calculated by [28]:

$$C_{ann,tot} = C_{cap} + C_{rep} + C_{O\&M} + C_{fuel} \quad (2)$$

where, C_{cap} is capital cost ($/yr.), C_{rep} is replacement cost ($/yr.), $C_{O\&M}$ is operating and maintenance cost ($/yr.), and C_{fuel} is fuel cost ($/yr.), if applied. Also, capital recovery factor is calculated as follows:

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (3)$$

where, i is, again, the annual interest rate (%) and N is the number of years [27].

Another economic term is levelized cost of energy (COE), which can serve as a useful metric to compare the energy costs of different systems. It denotes the average cost per kWh of useful energy produced by the system and is calculated by the following equation:

$$COE = \frac{C_{ann,tot}}{E_{load} + E_{g,s}} \quad (4)$$

where, $C_{ann,tot}$ is, again, the total annualized cost ($/yr.), E_{load} is the amount of load served by the system annually (kWh/yr.), and $E_{g,s}$ is the amount of energy sold to the grid per year (kWh/yr.) [27]. Although the COE is calculated by HOMER for different combinations of the system, the comparison and sorting of the system configuration, from the best to the worst, is carried out by NPC calculation.

The optimization process is accomplished within a set of steps to find the best MG configurations. In addition to the input data of components and resources, HOMER considers different constraints which are applied by the modeler. The overall optimization process is illustrated in Fig. 5.

4. OPTIMIZATION RESULTS AND DISCUSSION

Regarding the size options entered for components of the MG in the search space, HOMER evaluates all possible configurations and component sizes and calculates the total NPC for each mode to find the best answer for the optimization problem. Table 3 presents different combinations of the MG sorted considering the total NPC.

The following notes are extracted from the optimization results:

- As the capital cost for the diesel generator is set to zero, the least NPC belongs to the mode that DG is the only power generating unit. Here can be seen that the NPC is far less than other configurations. This is mainly because of zero capital cost of DG in the building and low price of diesel in Iran.
- The DG unit, in normal operating conditions, can meet the electrical demand with high reliability during the utility outage in a disaster.
- Adding a storage unit to the DG provides the second cost-effective configuration.
- In the combinations with the presence of PV and/or WT, their capacities are selected in the minimum value, i.e. 4 kW and 1 wind turbine.
- The most renewable energy fraction (12%) belongs to the case that both WT and PV are installed in the MG.

For the optimal case that all components of the MG are available, Fig. 6 shows the annual power production of the system. The output power of renewable devices increase as the renewable resources increase in mid-year. It is clear that in all months, the load is met completely by the MG power sources.

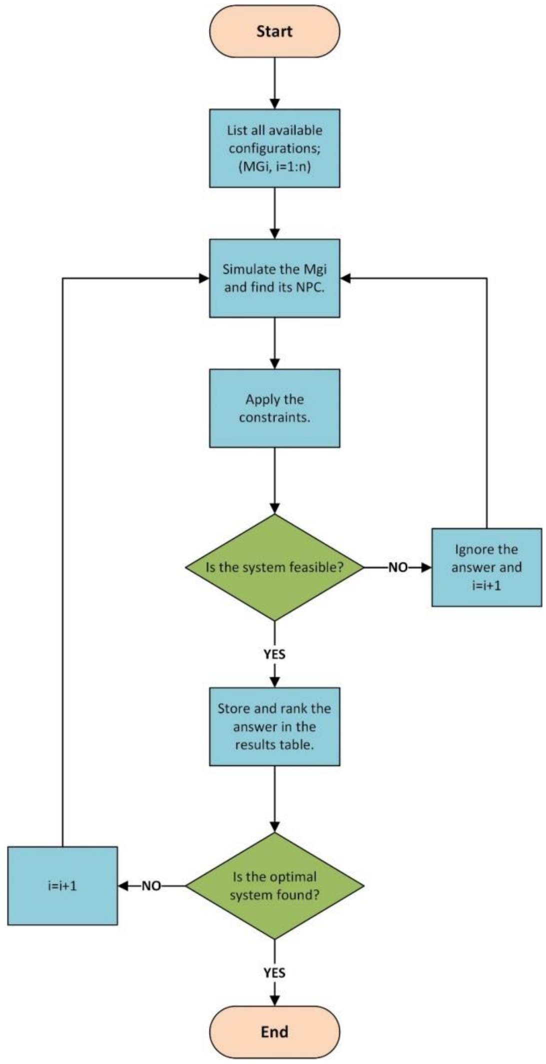

Fig. 5. The optimization flowchart

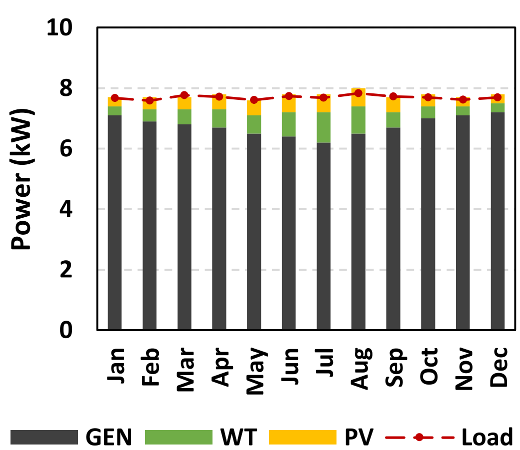

Fig. 6. Monthly average electric production by microgrid components

Table 3. Different combinations of the microgrid as the optimization results

PV (kW)	WT (units)	Battery (strings)	Converter (kW)	DG (kW)	Total Capital Cost ($)	Total O&M Cost ($/year)	Total NPC ($)	Renewable Fraction (%)
0	0	0	0	12	0	4534	47031.86	0
0	0	2	4	12	6600	4834	56743.27	0
4	0	0	4	12	11000	4511.8	57801.64	5.3
0	1	0	0	12	18000	4489.8	64573.48	6.96
4	0	2	4	12	16600	4771.8	66098.12	5.3
0	1	2	4	12	24600	4788.6	74272.95	6.98
4	1	0	4	12	29000	4472.8	75396.96	12
4	1	2	4	12	34600	4731.6	83681.51	12.01

As mentioned previously, the analysis is accomplished in two mid-winter and mid-summer cases. Fig. 7 and 8 illustrate the WT and PV output power, for the mid-winter and mid-summer cases, respectively.

From Fig. 7 and 8, it can be seen that a satisfying portion of the load can be met by renewable energy sources and the rest could be covered by the operation of diesel generator. The dotted line represents the total hourly renewable power production.

5. SENSITIVITY ANALYSIS

One of the most important factors that should be considered during the designing process of an energy system is the variability of different parameters. This may rise in projects in which reliability is of great importance. The system operation depends upon different variables which are uncontrollable by the user. These include changes in renewable resources, load demand, diesel price, etc. Therefore, to analyze and ensure the reliability and robustness of the system, a sensitivity analysis is indispensable.

Renewable resources variations are of major causes of unreliability in renewable power systems. While, the analysis in this project showed that slight changes in renewable resources do not affect intensely on the operation of the system. Therefore, these kinds of variations are not considered as sensitive variables.

In this paper, diesel price is considered as the most important factor that may influence on the system type and operation. In other words, it is assumed that in cases of emergency situations and natural disasters, a shortage in fuel supply may increase its price. Therefore, the main sensitivity variable considered in this paper is diesel price. The results of sensitivity analysis are depicted in Fig. 9 to 11.

It can be seen in Fig. 9 and 10 that an increase in diesel price will cause the feasibility of renewable-based system types. In other words, with prices up to 0.5-0.6 $/L, the only optimal power system is diesel generator. With prices more than this, wind and solar power sources should be added to the power system. Moreover, in certain diesel prices, resource variations may have slight impacts on the optimal system type.

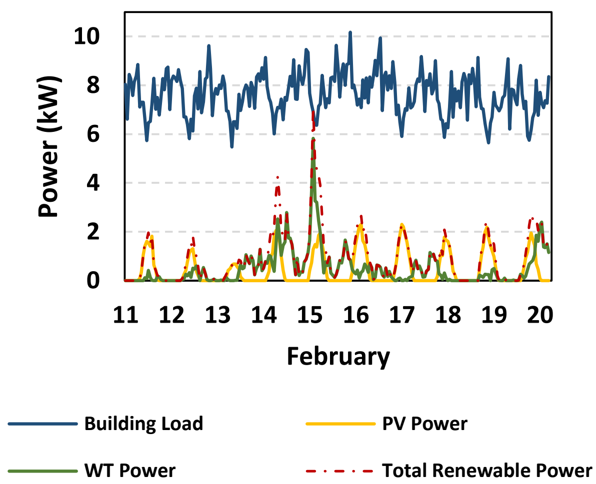

Fig. 7. PV and WT output power in mid-winter case

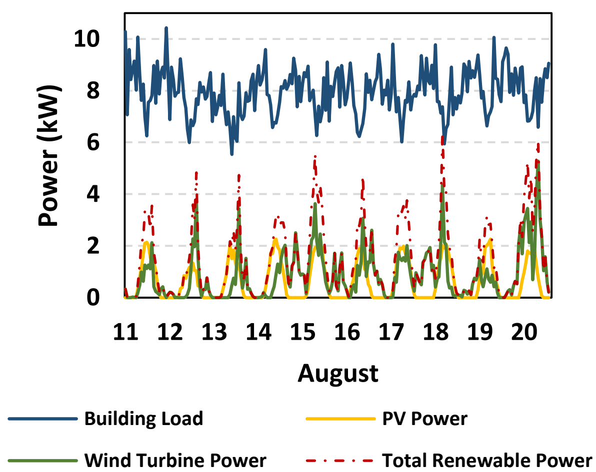

Fig. 8. PV and WT output power in mid-summer case

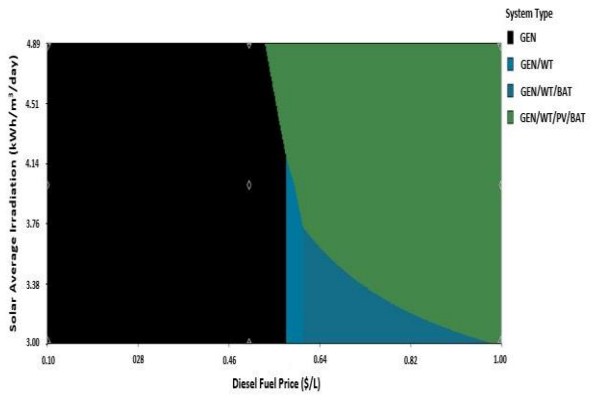

Fig. 9. Optimal system type with respect to diesel price and global solar irradiation

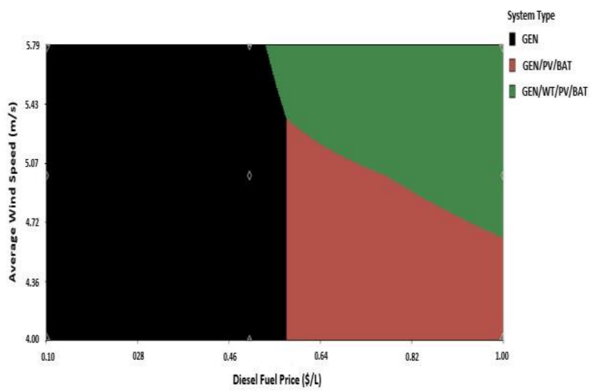

Fig. 10. Optimal system type with respect to diesel price and wind speed

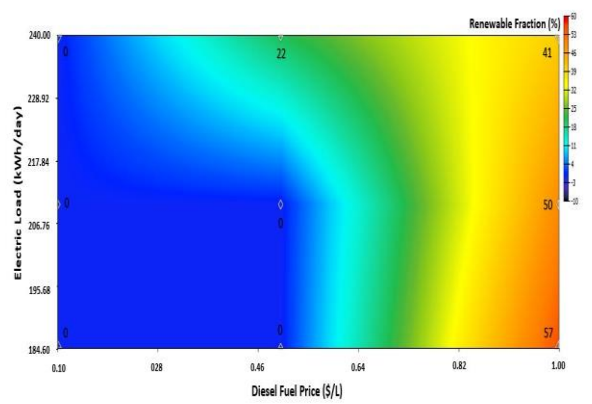

Fig. 11. Renewable fraction with respect to diesel price and building load

Fig. 11 shows the impact of diesel price and building load on the renewable fraction of the MG. The numbers written in the plot are the renewable fraction related to each value of load and fuel price. As of Fig. 9 and 10, increasing diesel price will lead to a rise in renewable fraction. For instance, in load value of 240 kWh/day, fuel price growing causes an increase of renewable fraction from 0 to 22 and then 41%. In contrast, demand increase has a different influence on the renewable fraction. In fuel prices less than about 0.6-0.7 $/L, renewable fraction increases as well as demand growth; while, in higher fuel prices, renewable fraction acts inversely comparing to demand. In other words, the highest value of renewable fraction can be achieved in low demand values (current load) and high fuel prices.

6. CONCLUSION

In this paper, a hybrid energy system is designed for a disaster management building of Tehran Disaster Mitigation and Management Organization (TDMMO). Some renewable resources options were suggested to cope with the installed diesel generator to increase the building energy system reliability and ensure an uninterruptable power supply, in disaster and emergency conditions. The proposed system architecture works suitably and meets the building demand.

As a brief conclusion, some notes may be regarded as follows:

- Low fossil fuels price in countries like Iran, is one of the main setbacks in spreading the use of renewable resources.
- Renewable power systems are good and reliable power backups for conventional power systems.
- Diversity in the energy supply of a system, from a critical building to the whole country, will lead to an increase in energy supply security, so that a potential shortage in one energy source may cause less adverse impacts on the system.
- For the studied building, in current diesel price and for diesel prices up to 0.5-0.6 $/L, a diesel generator is the optimal option for emergency off-grid situations.
- In any potential increase in price or shortage of diesel in disaster situations, PV and WT are good options to cope with the diesel generator to supply the building. As for a ten-fold increase in the diesel price, an average increase of zero to 50% will occur in renewable fraction.

As a future work, it is suggested to conduct the optimization with a meta-heuristic optimization algorithm to compare the results with current software optimal sizing.

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