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Fuel Consumption Reduction and Energy Management in Stand-Alone Hybrid Microgrid under Load Uncertainty and Demand Response by Linear Programming

A. Dejamkhooy[1, *], *M. Hamedi*[1, 2], *H. Shayeghi*[1], *S.J. Seyed Shenava*[1]

[1]*Department of Electrical Engineering, University of Mohaghegh Ardabili, Ardabil, Iran*
[2]*Ardabil Province Electricity Distribution Co., Ardabil, Iran*

Abstract- *A stand-alone microgrid usually contains a set of distributed generation resources, energy storage system and loads that can be used to supply electricity of remote areas. These areas are small in terms of population and industry. Connection of these areas to the national distribution network due to the high costs of constructing transmission lines is not economical. Optimal utilization and economic management of production units and storage devices are important issues in isolated microgrids. During optimum utilization, of renewable energy harvesting is maximized and fuel cost of diesel units reduces as much as possible. In this paper, the optimization problem is designed and solved as Linear Programming (LP). The cost of diesel generator unit depends on its production. Also, the fact is considered that the efficiency of diesel generator units is not constant for all amount of production. As a solution for this challenge demand side management plans have been proposed. On the other hand, load uncertainty is considered in this paper. Several scenarios are simulated by GAMS software for different conditions of a typical microgrid. The simulation results show the success of the proposed method in reducing costs and fossil fuel consumption and increasing the consumption of renewable energy.*

Keyword: Microgrid, Distributed generation, Demand side management, linear programming, Load uncertainty.

NOMENCLATURE

I	Set of diesel generators $\{DG_1, DG_2, \ldots, DG_I\}$
T	Set of time intervals in hours $\{t_1, t_2, \ldots, t_T\}$
$P_{LOAD,t}$	Load demand forecast at time interval t in kW
$P_{PV,t}$	Photovoltaic production forecast at time interval t in kW
SOC_{abs}^{min}, SOC_{abs}^{max}	Minimum and Maximum absolute BESS state of charge
$SOC_{1usable}$, $SOC_{Tusable}$	Initial and final value of relative SOC as percentage of usable energy
P_{BESS}^{min}, P_{BESS}^{max}	Minimum and maximum BESS power
$P_{DG,i}^{nom}$	Nominal power for DG_i
$E_{BESS,n}$	Nominal energy capacity of BESS
C_f	Cost of fuel in Euro per liter
E_{BESS}^{min}	Minimum value of BESS energy in kWh
E_{BESS}^{max}	Maximum value of BESS energy in kWh
$E_{BESS}^{max,usable}$	Range of usable BESS energy in kWh
$P_{BESS,t}$	BESS power at time interval t in kw
$P_{DG,t,i}$	DGi power at time interval t in kw
SOC_t	storage charge level at time interval *t* in p.u.
$E_{BESS,t}$	BESS energy at time interval *t* in kwh
E_{DG}	Total DG daily energy produced in kWh

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∗Corresponding author:
E-mail: majiddejam@uma.ac.ir (A. Dejamkhooy)
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1. INTRODUCTION

Basic priority of developing countries is allocated to expand access to clean electricity and other electricity generation equipment for remote areas [1]. Access to this purpose is part of the Sustainable Development Goals (SDGs) [2]. Seventh generation SDGs focus on universal access to high reliability energies [3]. However, until recent 2014, about one billion people (about 15% of the world's population) still had no access to electricity [4]. This lack of access to electricity sources is mainly seen in remote rural areas that are geographically and economically unable to connect to the grid.

Global efforts are done with electrification these areas separately from electricity gridlines. Between 2008 and 2017, the capacity of renewable off-grid energy sources has become 300 times, which is equivalent to 6.5 GW [5]. The use of renewable energy technology in the local energy sector has caused a significant reduction in the amount of carbon (that is used) in energy production [6].

Renewable energy systems are highly dependent on climatic and climate conditions, and therefore their amount of energy generation varies. In contrast, hybrid systems, due to the combination of renewable energy resources with traditional systems, with lower cost and energy loss and greater compatibility with uncertainty factor especially in remote areas, can have better performance [7, 8]. Isolated renewable energy generation systems vary widely depending on local and communication facilities. Over the past decade, the increasing demand for using solar energy led to the emergence and production and growth of photovoltaic systems [9]. However, little research has been done on small power plant systems based on multipurpose production systems for remote human societies. A multipurpose generation of electricity, cooling and ethanol by sunlight and biomass for an off-grid faraway human society in India using LP method to determine optimal size of system by maximizing annual profit and maximum utilization of local resources has been conducted in Ref. [10]. According to this, a software program has been designed that enables consumers to achieve the management of electricity in a multipurpose microgrid with the aim of minimizing electricity bills [11]. Recent studies to optimize the design of multipurpose power plant systems led to the use of fuzzy optimization methods. The formulations of the above method are presented in Ref. [12]. A similar fuzzy linear programming method is presented in Ref. [13]. This problem of optimizing energy generation in multipurpose systems has been later performed by fuzzy mixed integer linear programming method [14]. In Ref. [15], using a mixed integer linear programming method, an optimal co-generation system has been set up. The P-GRAPH method has been used for a similar problem with the aim of demonstrating that this method is more effective than the MILP method [16]. The fuzzy linear programming model, in order to optimally design a Combined Cooling Heating and Power (CCHP) system by considering environmental demand and constraints is applied [17]. Also, the same previous model with variation of product price is applied for power plants of triple optimum generation (electricity, cooling and heating) in Ref. [18]. Authors in Ref. [19] present the problem of micro-grid optimization by applying demand-side management and multiple objectives to reduce operating cost and customer dissatisfaction using genetic algorithm.

Regarding to the importance and necessity of reliable, sustainable, economical electricity supply and environmental considerations for residential areas away from main grids, various research have been carried out worldwide in previous years on utilizing microgrids. The review of previous researches shows that different methods have been employed to achieve those objectives in microgrid design. In which, the issues of demand side management, load uncertainty, and the variability of diesel generators efficiency in different amounts of power generation are less investigated.

In this paper, a stand-alone microgrid, which installed to supply electrical power of a remote area, is investigated. It includes diesel generator units, photovoltaic units, and storage system. Two objective functions have been defined and solved with linear programming in GAMS for economical operation and energy management. The first objective function deals with maximum harvesting by PV system and then minimum production by diesel generators. The key point that causes to continue this investigation and suggest the second objective function is that necessarily reducing the production of diesel units does not mean reducing fuel consumption. It is because that the efficiency of the diesel units depends on their production amounts directly. In other words, more fuel is consumed in low productions of diesel generator units. Therefore, in the second objective function, the goal is to minimize the fuel consumption of diesel generator units by considering variability of their efficiency. To overcome to this challenge a Demand Response (DR) plan is proposed. Also, the microgrid load uncertainty is considered in this study.

The main contributions of the paper can be summarized as:

1. Maximum amount of the renewable energy in a hybrid stand-alone microgrid is harvested.
2. Actual efficiency of the diesel unit, which depends on its generated power, is considered. In other words, the diesel unit efficiency is not fix value for different output powers. This fact, which happens in practices, is regarded.
3. Since the diesel unit efficiency is not fix value, based on experimental results the diesel unit consumes lower fuel for high amount of the output

generated power. Therefore, low generation of the diesel unit does not lead to low fuel consumption. Another novelty of the paper is a schedule that can reduce fuel consumption of the units.

4. The fuel consumption reduction is achieved by a Demand Response (DR) program.
5. Load uncertainty in the stand-alone microgrid is considered.

The rest of the paper is organized as below. In the next section diesel generator properties are presented. Problem formulation is given in section 3. The investigated stand-alone is introduced in section 4. Simulation results and discussions are presented in section 5. Finally, section 6 summarizes the paper.

2. DIESEL GENERATORS IN THE MICROGRID

In this paper, the studied microgrid includes a number of diesel generator, solar power plant, energy storage batteries and household load as shown in Fig. 1, that specifications of each of them is described in detail in section 4. Also, the efficiency and fuel consumption of diesel generators in term of the generated power are shown in Fig. 2. For the studied grid, the relationship between power of diesel generators and of fuel cost is as

$$C_{fuel_{t,i}} = \left(A + BP_{DG,t,i}\right)C_f \qquad (1)$$

Where A = 13.717 L/h and B = 0.22246 L/kWh are constant coefficients. P DG, t, i is power of DG_i at time interval t and C_f = 0.75 €/L. diesel heating value and diesel density are 40.9 Mj/kg and 835 kg/m3 respectively. If the fuel consumption rates for different generated power of the diesel generators are given, the input power for DGs and the corresponding efficiency can be calculated [20]. Therefore, if microgrid has several diesel generators, different powers and consequently different efficiencies can be observed by diesel generators for a certain amount of load. In this study, it is tried to present strategies to reduce costs of diesel generators.

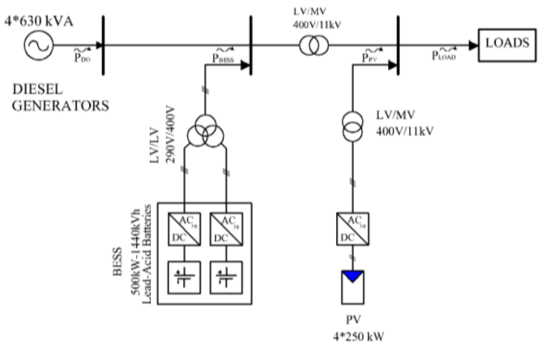
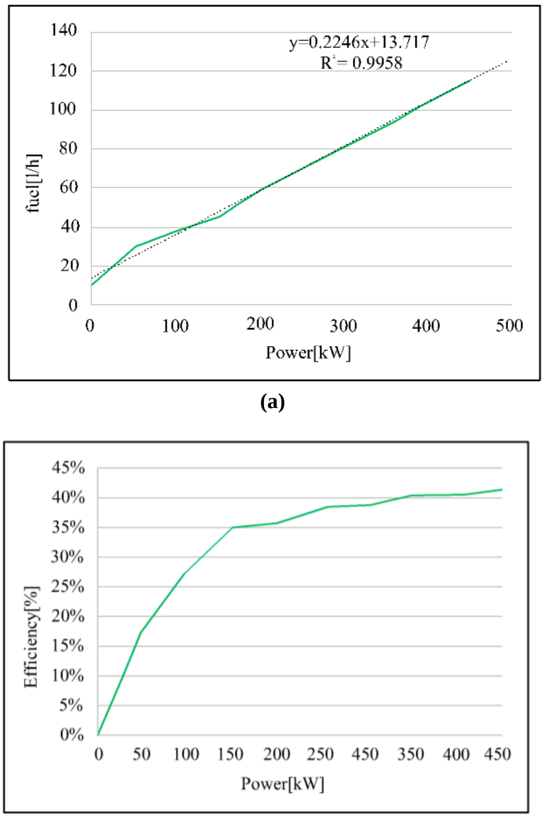


Fig. 1. Schematic of the studied microgrid



(b)

Fig. 2. Variation of fuel consumption and efficiency of the diesel generator in terms of generated power of diesel
(a) Fuel consumption (b) efficiency

For this purpose, in addition to the objective function for minimizing power generated by diesel generators, the second objective function based on fuel consumption minimization has been developed. It includes a consumption management program, which moderates variety of diesel generator efficiency.

3. PROBLEM FORMULATION AS A LINEAR PROGRAMMING

Linear Programming (LP) is predicated to a category of optimization problem, where the objective function and the constraints are linear function of real decision variables. Both of the optimization problems in this paper can be considered as LP.

In this paper, the optimization problems in LP form are solved by GAMS/Cplex. It is a GAMS solver that allows users to combine the high level modeling capabilities of GAMS with the power of Cplex optimizers. Cplex optimizers are designed to solve large, difficult problems quickly and with minimal user intervention [21].

Cplex solves LP problems using several alternative algorithms. The majority of LP problems solve best using Cplex's state of the art dual simplex algorithm.

Certain types of problems benefit from using the primal simplex algorithm, the network optimizer, the barrier algorithm, or the sifting algorithm. The concurrent option will allow solving with different algorithms in parallel [21].

3.1. The first objective function

Since the first objective of optimization is to obtain as much energy as possible from renewable energy sources, the first objective function is set as equation (2) with the aim of reducing the amount of energy generated by diesel generators over a specified time period T = 24h.

$$\min(E_{DG}) = \sum_{t=1}^{T}\sum_{i=1}^{l} P_{DG,t,i} \quad (2)$$

Also, the constraints of this objective function, including equal and unequal constraints, are discussed in below.

3.1.1 Balance of the power flow

The absorbed power by load at any given interval must be equal to the sum of the power obtained from BESS, PV and DG.

$$\sum_{i=1}^{l} P_{DG,t,i} + P_{pv,t} + P_{BESS,t} - P_{Load,t} = 0 \quad (3)$$

3.1.2 Maximum available energy for storages

This value is obtained from the multiplication of nominal storage energy in the difference between the maximum and minimum storage levels (SOC) as

$$\sqrt{E_{BESS}^{\max,usable} = (SOC_{abs}^{\max} - SOC_{abs}^{\min}).E_{BESS,n}} \quad (4)$$

3.1.3 Set the initial and final SOC values

The charge level at the beginning and end of the study period will be based on the percentage of available useful energy is according to (5) and (6).

$$SOC_{usable,t=1} = SOC_{1,usable} \quad (5)$$

$$SOC_{usable,t=T} = SOC_{T,usable} \quad (6)$$

3.1.4 Energy of storages

The consumption of the energy of batteries in the microgrid at different operating hours is obtained from the equation (7). In this equation, the absorption power is considered with a minus sign and the injection power to the microgrid is considered with positive sign and also to reduce the available energy, power is reduced from the energy at the time interval t.

$$E_{BESS,t+1} = E_{BESS,t} - P_{BESS,t}.\Delta t \quad (7)$$

3.1.5 Constraints of diesel generator power

The power of DGs is limited by the maximum and minimum generation of the generator, which is achieved by the rates set by the manufacturer.

$$P_{DG,i}^{\min} \le P_{DG,t,i} \le P_{DG,i}^{\max} \quad (8)$$

3.1.6 Storage power constrains

Battery power is also determined by the highest positive and negative values of the inverter power, as well as the maximum capacity of batteries (C_{rate}).

$$P_{BESS}^{\min} \le P_{BESS,t} \le P_{BESS}^{\max} \quad (9)$$

3.1.7 Maximum and Minimum Energy of Storage (BESS):

The energy range of storages is determined by the battery manufacturer's recommendation and depending on its technology.

$$0 \le E_{BESS,t} \le E_{BESS}^{\max,\text{usable}} \quad (10)$$

3.2. The first objective function

In the second objective function, the ultimate goal is to minimize the amount of fossil fuel consumption of diesel generators in terms of all previous constraints as

$$\min(\text{Fuel}_{DG}) = \sum_{t=1}^{T}\sum_{i=1}^{l} L_{DG,t,i} \quad (11)$$

where $L_{DG,t,i}$ is fuel consumption of i-th diesel unit at interval t. l and T are total number of the diesel units and time intervals, respectively.

In this paper, the second objective function is more comprehensive than the first one. Thereby, integration of them in an objective function as multi-objective is not possible. In other words, the first objective function is conducted to show that reduction of participation of the diesel units in supplying the load is not desirable necessarily. This result leads us to design and solve the second objective function.

DR program as a portion of the solution is utilized in the second objective function, where the aim is fuel consumption reduction in the diesel units. Developing DR program in a stand-alone microgrid not only for economic aspects but also for fuel consumption reduction has been rarely investigated.

In this condition, minimizing fuel consumption through the DR program for microgrid consumers will be conducted to operate the diesel generators at high efficiency (curve in Fig. 2-a). The employed DR program can be defined as

$$P_{i,h}^{D} = (1 - DR_h) \times P_{i,h}^{D} + ldr_h \quad (12)$$

$$P_{i,h}^{D} - P_{i,h}^{DR} = ldr_h = DR_h \times P_{i,h}^{D} \quad (13)$$

Where $P_{i,h}^{D}$, is the initial load demand in the time interval h and $P_{i,h}^{DR}$ is the load after executing the DR program in the same time interval. ldr_h and DRh show the amount of load shifted at time interval h and the coefficient of subscriber participation in DR operations respectively [22].

In this DR, the amount of the shifted load for the daily period will be equal to zero as

$$\sum_{h=1}^{N_h} ldr_h = \sum_{h=1}^{N_h} DR_h \times P_{i,h}^D = 0 \tag{14}$$

Also, the maximum value of DR_h in each interval is showed by DR_{max}, and then

$$DR_h \le DR_{\max} \tag{15}$$

3.3. Load uncertainty modeling

In this paper, it is assumed that the load can be uncertain. It is assumed that the predicted load value has an error with the specific probability distribution function derived from past experiments of the microgrid consumption. The probabilistic curve schematic, which is used in this paper with the 20% load consumption tolerance, is shown in Fig. 3.

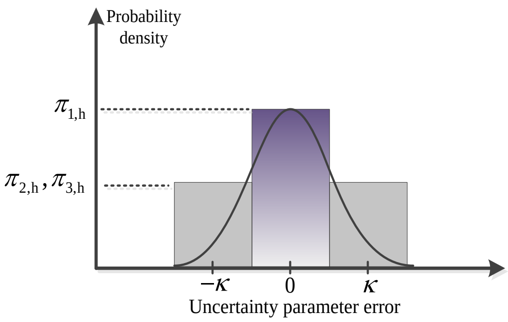


Fig. 3. Probabilistic distribution of prediction error

The probabilistic power value at time of h, which is the sum of a base value with a random number, can be written as

$$P_{h,s}^D = P_{h,s}^{D_{forecasted}} + \Delta P_{h,s}^D \tag{16}$$

Where $P_{h,s}^D$ is the prediction error rate. It is divided into three parts. The mean error value is equal to zero and the probabilities of a positive and negative error are equal together and both values are assumed to be K. In other words, the value of K is equal to the standard deviation [23].

4. STUDIED MICROGRID

A hybrid standalone microgrid is studied in this paper, which is shown in Fig. 1. It includes four diesel units of 630 kVA / 500 kW, a 1 MW renewable power plant consisting of four photovoltaic units each with a capacity of 250 kW, and the Battery Energy Storage System (BESS) as 2 × 250 kW and 2 × 720 kWh BESS. The BESS made of two lead-acid battery banks for a total of 600 lead-acid batteries, where each battery is characterized by a rate voltage 2 V and rated capacity of 1200 Ah. Each battery bank is connected to the microgrid via a DC/AC 250 kVA bidirectional inverter.

The main task of BESS is to cover the uncertainty of renewable resources, to improve the stability of the power system and to reduce the cost of operating the microgrid system. The power plant has been designed to power the microgrid consumers using the three main feeders of distribution in medium voltage level (50 Hz, 11 kV). 24-hour load profile of the grid is shown in Fig. 4. For a sample day, generated power by the PV units is shown in Fig. 5. It is assumed that the MPPT mechanism has been employed.

The measurement results of the microgrid production resources on the sample day are given in Table 1. These amounts are utilized to manage power flow and maximize use of renewable resources and reduce diesel generation and fuel consumption. In other words, via solving the optimization problem, which constructed as linear programming and conducted by GAMS, these parameters should be improved.

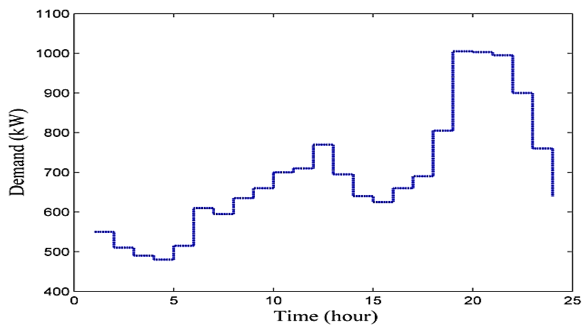


Fig. 4. Daily chart of load

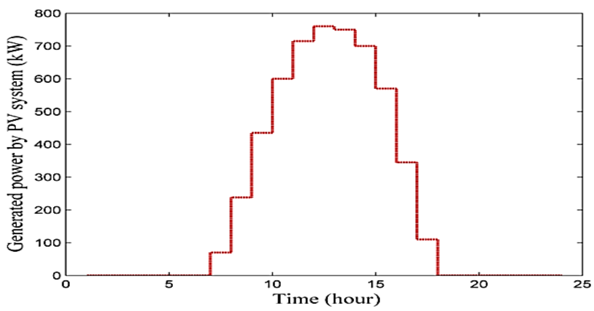


Fig. 5. PV hourly production

Table 1. Measurement results of the study system on sample day

Data	Measure of case study
Generated energy by DG units (kWh)	13361
Generated energy by PV units (kWh)	1131
Daily fuel cost of DG (€)	2699

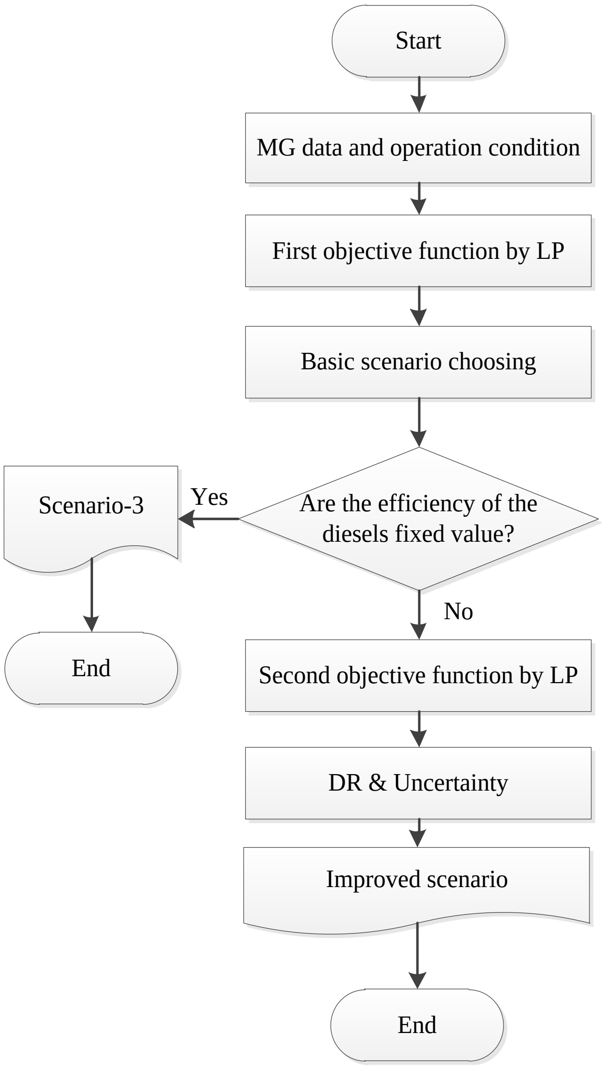


Fig. 6. Flowchart of the proposed schedule

5. SIMULATION RESULTS DISCUSSION

The simulations are performed on the studied system for two different objective functions.

In the first objective function by suggesting three scenarios, it is attempted to maximize the use of solar energy and to minimize the amount of generating energy of diesel generators. In the second objective function by considering variety of diesels efficiency, fuel consumption of the diesel units is aimed to be reduced. During this objective function, demand response program is run. The flowchart of the proposed schedule is illustrated in Fig. 6.

5.1. Simulation of the first objective function

In the first objective function, the maximum utilization of PV power is investigated. As Fig. 5 shows, the PV power is precisely corresponding to the solar power plant's field metering capability equipped with MPPT. To investigate the different modes in this objective function, three scenarios are designed as follows:

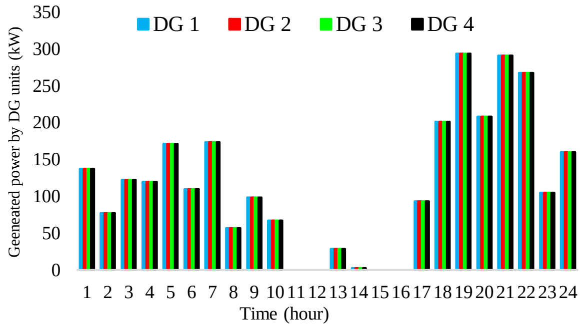


Fig. 7. The daily production of diesel generators, scenario 1

Table 2. Energy production and fuel consumption, scenario 1

Data	Measure of case study	LP
Generated energy by DG units (kWh)	13361	10390
Daily saved energy (%)	-	28.5
Generated energy by PV units (kWh)	1131	0
Daily fuel cost of DG (€)	2699	2865.84
Saved cost of DG units (%)	-	- 6.18

Scenario 1: Diesel generators work concurrently in parallel and under the same load.

Scenario 2: Diesel generators work concurrently in parallel and under optimally dividing load.

Scenario 3: Diesel generators can either be switched on or off independently.

5.1.1 Scenario 1

In this scenario, it is assumed that all diesel units are always on and ready for operation and load are equally distributed between them. The advantage of this scenario is the ability of the set to supply maximum load and none of the generating units will overload. After solving LP, DG hourly power and then the grid energy data are presented in Fig. 7 and Table 2, respectively.

5.1.2 Scenario 2

In this scenario, it is assumed that all diesel units (which are technically identical) are always on and ready for operation, but their load is divided according to the optimum fuel consumption per unit. In other words, since the efficiency of the units is maximized around the nominal capacity, so until a unit is not reached its nominal capacity, the next unit will not be under load but all units are ready to start. The results for this case for how to manage dispersed production resources and the rate of change in variables are presented in Fig. 8 and Table 3. As shown in Fig. 8, it is clear that until a diesel generator does not reach to its nominal capacity, the next unit will not be switched on. In this case, although diesel generators produce more power than the former, but the cost has not changed.

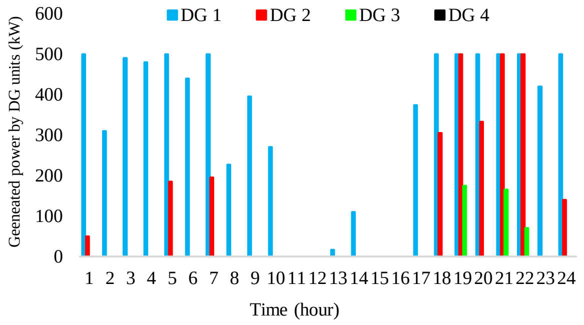


Fig. 8. The daily production of diesel generators, scenario 2

Table 3. Energy production and fuel consumption, scenario 2

Data	Measure of case study	LP
Generated energy by DG units (kWh)	13361	11150
Daily saved energy (%)	-	20
Generated energy by PV units (kWh)	1131	0
Daily fuel cost of DG (€)	2699	2865.84
Saved cost of DG units (%)	-	- 6.18

In this scenario while generation of a diesel unit does not reach to maximum value, other unit does not start to production. The reason is that the high efficiency of each diesel unit occurs in its high generation amount. Therefore, this scenario endeavors to utilize each unit at its maximum capacity before loading other one.

5.1.3 Scenario 3

In this scenario, it is assumed that each unit in any time that is needed can be switched on. And also, total load would be divided into units depending on the optimal fuel consumption. In other words, until the unit or units are not reached their nominal capacity, the next unit will not be switched. The positive feature of this case is to increase efficiency and reduce fuel consumption, but the set is not robust to sudden changes in load compared to the other two. The results for this case for how diesel generators are managed and the amount of delay in the energy parameters are presented in Fig. 9 and Table 4. As shown in Fig. 9, it is clear that another unit will not start operating until the diesel generator reaches its nominal capacity. In this case, although the dispersed generating units produce the same energy than the second case, the fuel cost is lower. This is due to the use of switching off the other units in supplying load.

In the first scenario, since the LP requires continuous parameters and cannot operate in a discontinuous performance, it does not allow to the diesel generator to be on and off. They must produce at a constant rate continuously. When low power is needed then the diesel generator operation point will be set to the lowest set value (less than 5% nominal power). In such condition, their fuel consumption increases. It can be seen in Fig. 9, the position of the diesel generator is at low production conditions for a period of less than 45% of the daily time interval. As expected, minimizing the energy production of diesel generators will not result fuel consumption reduction and subsequent costs.

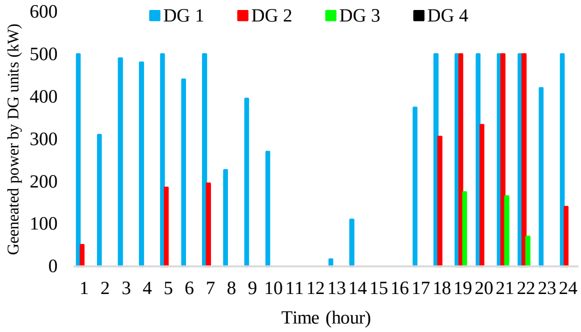


Fig. 9. The daily production of diesel generators, scenario 3

Table 4. Energy production and fuel consumption, scenario 3

Data	Measure of case study	LP
Generated energy by DG units (kWh)	13361	11150
Daily saved energy (%)	-	20
Generated energy by PV units (kWh)	1131	0
Daily fuel cost of DG (€)	2699	2248.57
Saved cost of DG units (%)	-	16.68

In scenario-1 (Table 2), in spite of reduction of the diesel unit generations, LP causes to increase fuel consumption and related cost. There is the same condition in scenario-2 (Table 3). The reason (as expected) is that the reduction of the diesel unit generations, which is resulted by maximizing PV penetration, does not lead to fuel consumption reduction necessarily. Because that low amount of the diesel unit generation means their operation in low efficiency. (See Fig. 2) In scenario-3 (Table 4), LP can reduce generation of the diesel units and their fuel consumptions simultaneity. Therefore, the scenario-3 is adopted as basic scenario for continuing the study e.g. in the second objective function.

5.2. Simulation of the second objective function

In the second objective function, the aim is to minimize the amount of diesel fuel consumed by executing demand response program. A condition similar to first scenario is assumed and simulated. The results for diesel generator productions with and without the DR program are demonstrated in Fig. 10.

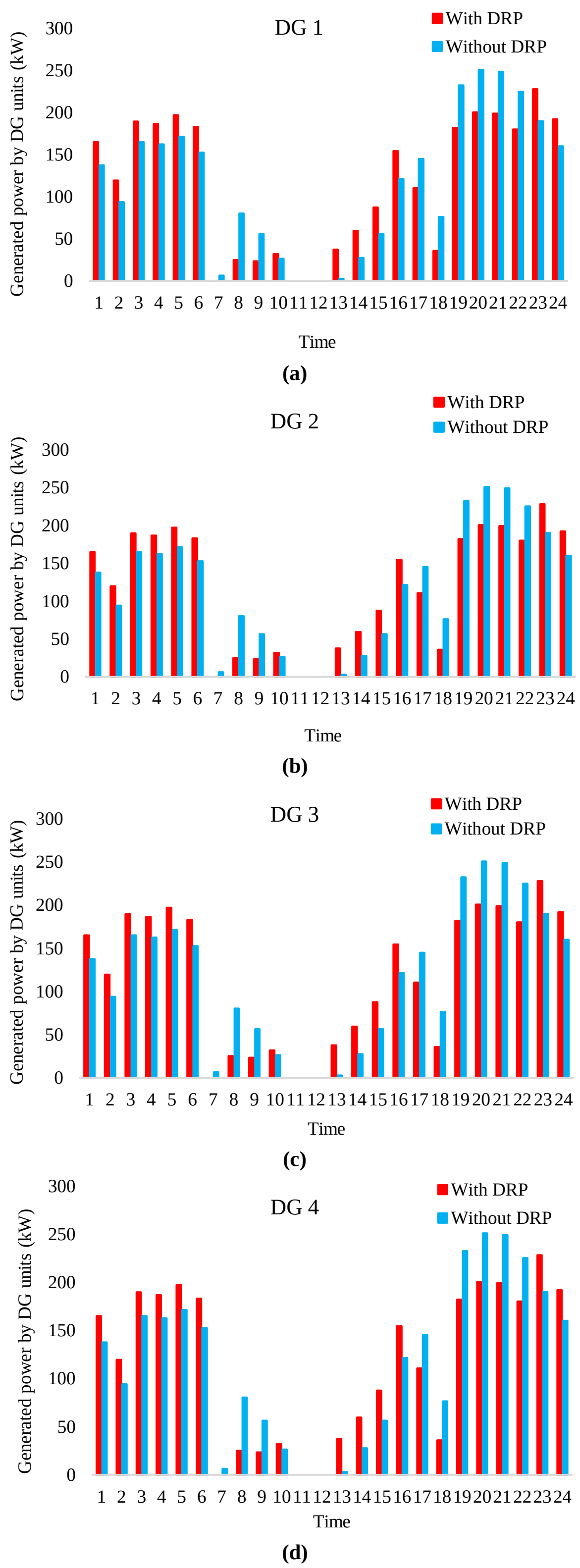


Fig. 10. The daily production of diesel generators with and without DR. (a) DG1, (b) DG2, (c) DG3, (d) DG4

Generally, demand side management program is run in conventional grids to reduce peak consumption. But in the proposed method, it has been executed to minimize fuel consumption. By using (1), the total cost of fuel with and without considering demand response program are calculated as € 2879.920 and € 2955.891, respectively. Therefore, by implementing the second objective function, fuel cost under the demand response programs id reduced by 2.57%. The results show that the use of load management programs has a significant impact on the rate of fuel reduction. Also compared to the first scenario of the first objective function, some grid parameters are improved.

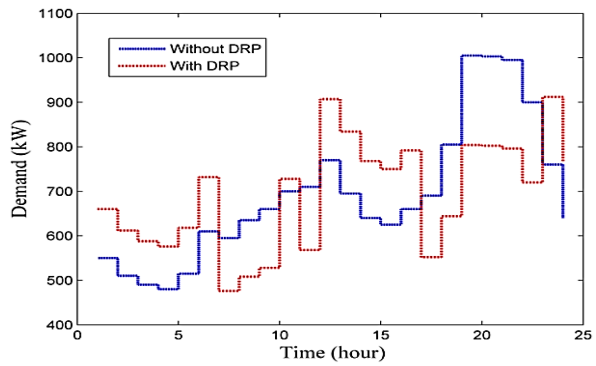


Fig. 11. The microgrid load with and without the DR program

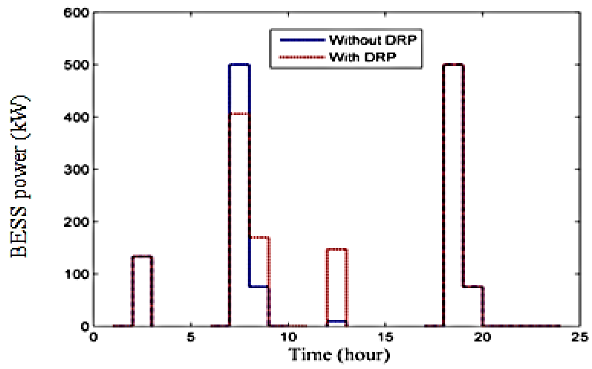


Fig. 12. Power of the storage with and without DR program

Table 5. Energy production and fuel consumption, scenario 3 with DR and load deviation

	scenario 3	scenario 3 with 20% load decrease	scenario 3 with 20% load increment
Daily fuel cost of DG (€) without DR	2248.576	1898.656	2637.72
Daily fuel cost of DG (€) with DR	2137.54	1846.224	2483.355
Saved cost of DG units (%)	5.19	2.76	6.21

Regarding to this fact that solar radiation and consequently generation of PV units and consumption of major loads of microgrid are out of control, it is assumed that control strategy will be applied to diesel generators, batteries and a small fraction of the load. The load of microgrid with and without the DR program is presented in Fig. 11. Charged and discharged states of batteries are shown in Fig. 12. To investigate the uncertainty of the load, it is assumed that the probability distribution of the load error is a normal distribution with a mean of zero. Also, the minimum and maximum deviation can be equal to 20% of demand. To evaluate the performance of the DR and considering uncertainty, the simulation of the scenario 3 is repeated. The results are given in Table 5. By decreasing demand, saved cost decreases from 5.19% to 2.76%. Vice versa by increasing demand, saved cost increases from 5.19% to 6.21%. Circumstance of these variations deal with this fact that high efficiency and low fuel consumption of diesels occurs in high output power. On the other hand, according to Fig. 2, slope of the fuel consumption curve is high for low output power. However, it becomes gentle for high output power. Therefore, saved cost amount for the load increasing or decreasing are different.

6. CONCLUSIONS

This paper investigates the energy management of a hybrid microgrid by using linear programming. Two different objective functions based on minimizing the production of diesel generator units and minimizing the fuel consumption of diesel generator units have been presented. The impacts of demand response program and load uncertainty have been considered. The simulation results show that the rate of diesel generator energy production and fuel cost in scenario 3 of the first objective function are decreased by linear programming compared to field measurements with conventional management system 20% and 16.6%, respectively. Also, by applying DR to third scenario of the first objective functions (the same as the second objective function) savings of 5.19% in diesel generator fuel costs is yielded. The proposed approach can be employed for similar microgrids at remote areas.

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