Energy Dispatch of Decentralized Hybrid Power System

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Abstract- The continuous geometric growth in energy demand coupled with high operation cost of power systems have made renewable energy sources (RES) more attractive. This paper presents an optimal design and energy management strategy of photovoltaic-diesel-battery (PDB) decentralized hybrid power system (DHPS) that minimizes operating costs and provides reliable power supply. The nonlinear objective cost function is formulated for the economic dispatch problem taking into consideration various operating constraints. The diesel generator (DG) minimum operation efficiency is expanded and solved using Newton-Quasi method. The DG is constrained to operate between the proposed minimum and rated efficiency during its operation in order to achieve desired load factor. Mixed integer nonlinear programming (MINLP) technique is explored to optimize the utilization of RES in supplying the load demand reliably. A combined dispatch strategy which minimizes daily fuel consumption cost by the maximization of RES using a set of prioritized rules was developed and compared with the MINLP technique. The performance of the proposed combined strategy is validated by simulating the following operating scenarios: single household and community daily load profiles. The results show the effectiveness of the proposed combined dispatch algorithm as it reduces DG fuel consumption cost and improves supply reliability. Consequently, the effectiveness of these strategies encourages the integration of DHPS in remote and isolated communities.

Keywords photovoltaic-diesel-battery, decentralized hybrid power system, Newton-Quasi method, minimum operation efficiency, battery energy storage system, Energy dispatch strategy.

1. Introduction

Electricity demand has been on a geometric increase due to exponential population growth, unprecedented industrialization, vast innovations and widespread technological developments. Research has further shown that about 1.5 billion people lack access to electricity in the world, with about half of this population living in Africa [1]. The conventional power systems which are used to supply electrical loads depend on expensive, exhaustible fossil fuels [2][3]. In many countries, lack of sufficient financial resources and huge power losses also pose critical limitations to the utilization of these systems [4]. Thus, the diesel generators (DGs) have been generally employed to supply isolated loads, running continuously with a significant fuel consumption and enormous carbon-dioxide emission, especially at low efficiency [5][6]. Consequently, electricity becomes unaffordable and inaccessible.

However, sustainable and economically viable power supply can be provided through the incorporation of a DG with photovoltaic (PV) system and battery energy storage system (BESS), otherwise referred to as decentralized hybrid power system (DHPS) [7]. The benefits of such system include easy modularity, reduced operational and maintenance costs, inexhaustible natural resources, minimum environmental pollution, appreciable reliability level and close proximity to end-users [8][9]. In DHPS, the BESS is usually incorporated as energy backup for power balance regulation through absorption and dissipation of surplus power. Nevertheless, the PV power generation depends on the dynamic nature of weather conditions and thus, limits its capacity to provide 100% supply reliability [10][11]. On the other hand, dummy loads are usually connected to the DHPS in order to dissipate surplus power and achieve high operational efficiency [11][12]. This technique is energy and cost inefficient. Therefore, an optimal design and economically viable dispatch technique becomes indispensable for supply reliability and economic operation of DHPS.

The various optimization techniques which have been exploited in the energy dispatch of DHPS include but not limited to nonlinear programming (NLP) [4], mixed integer non-linear programming (MINLP) [10], model predictive control (MPC) [13], FMINCON and mixed integer linear programming (MILP) [14][15], sequential quadratic programming (SQP)[16], Genetic Algorithm (GA) [17][18], particle swarm optimization (PSO) [19][20], symbiotic organisms search (SOS) algorithm [21], harmony search (HS) algorithm [22], sequential quadratic programming (SQP) [23], fuzzy logic methods [24] and cycle charging strategy [25]. The literature reviews provide the basic theoretical background and useful energy dispatch strategies upon which this study will stand. Nonetheless, these methods have their weaknesses which include intensive investment cost and excessive DG ON/OFF control [5], abnormal state of charge limits [15], high computational analysis and slow convergence [17]-[22], assumption of unrealistic constant and random daily loads [20][24], loss of supply probability (LOSP) [26], dumping of excess energy [27]-[28], components oversizing [29][30] and assumption of various DG operation efficiency without any justification [5]-[31]. It is therefore evident that the authors of the reviewed literatures did not address the minimum operation efficiency of the diesel generator. This is however essential for the techno-economic operation of the system. The hybridization of these dispatch techniques can provide a robust dispatch energy technique.

This current study, therefore, addresses the mentioned knowledge gaps by proposing an economic energy dispatch and management strategy of decentralized hybrid power system which incorporates a minimum operation efficiency of the DG based on Newton-Quasi method. The closed loop PID feedback control system is modeled to regulate the PV generated power without violating its generation limit. A combined dispatch strategy which involves load following, cycle charging and discharging strategies is further proposed for the optimal operation of the system. The proposed techniques aim to provide affordable and reliable supply through the maximization of RER, without violating operational constraints. The results of both methods are tested with single household and community daily load profiles.

The paper is divided into six sections. The hybrid power system and its components are explained in section *II*. Section *III* presents optimization models which comprise of the MINLP and the proposed combined dispatch strategy. Section I*V* presents to case studies, model parameters and contribution factor. Section *V* present and discuss the simulation results. Section *VI* concludes and recommends future work.

2. Hybrid Power System Model Description

The models in [5] and [10] were considered in coming up with the proposed model. The proposed decentralized hybrid power system consists of three main sub-systems which include: the photovoltaic (PV) system, diesel generator (DG) and battery energy storage system (BESS) as shown in Fig. 1. The combined output power from the PV system and BESS is first maximized before the DG can be consider to supply the load. The BESS complements the PV system to supply the deficit power whenever the PV output proves could not meet the load demand. The DG is incorporated as secondary backup to provide reliable power supply and/or recharge the BESS whenever supply exceeds demand. The bi-directional converter converts BESS output from DC-AC and vice-versa during charge and discharge process respectively. The DC-AC inverter converts DC PV output to meet the AC load.

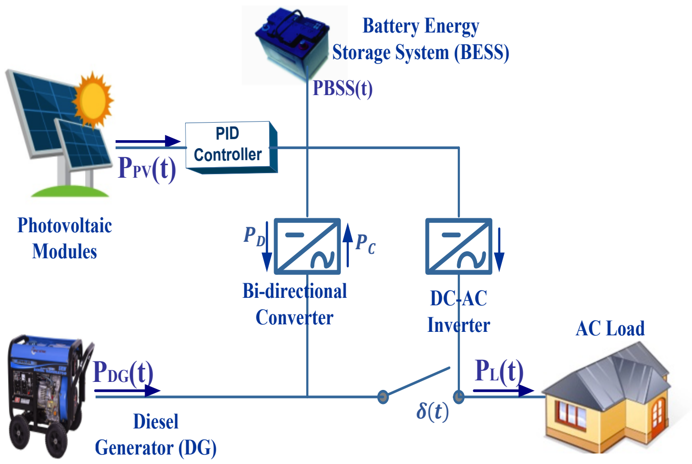


Fig. 1. Proposed PDB decentralized hybrid power system.

2.1 *Modelling of Photovoltaic* (PV) *System*

The photovoltaic system consist of a group of electrically interconnected series and parallel solar photovoltaic panels which generates direct current as a result of photo-electric emission incident on the semiconductor plate of the panels. These solar panels with specified capacity and configurations are usually arranged in order to produce desired voltage, current and power under standard test conditions in order to match the expected load. Therefore, the controllable PV output power which depends on the flexible ambient temperature and incident solar radiation can be computed as follow [32]:

$$P_{Pv}(t) = N_{pvs} N_{pvp} I_{SC(t,\varnothing)} V_{OC}(t)\ FF \qquad (1)$$

where $Npvs$ and N_{pvp} represent number of PV modules connected in series and parallel respectively; $V_{OC}(t)$ and $I_{SC(t,C)}$ represent open-circuit voltage and short-circuit current of a single module at any instant t and tilt angle $\varnothing$

respectively; *FF* represents the module fill factor. The solar radiation and ambient temperature data used in this work were obtained for Soshanguve, a typical South African remote community via the Centre for Energy and Electric Power (CEEP).

2.2 Modelling of Diesel Generator (DG)

The diesel generator is an electro-mechanical system comprising of an electric motor and a diesel engine that converts kinetic energy in its moving parts (prime mover) into AC electrical power and, conveys the generated power through the power cables. The electrical output power of the DG is significantly influenced by its specification, nonlinear electrical load and rotor speed control of the prime mover.

In this study, the variable speed DG is incorporated as a secondary backup power source to provide reliable supply as well as cover the net load, especially when the load demand exceeds PV output. The DG fuel consumption can be computed, as in Eq. (2) [21][33]:

$$C_f = \sum_{t=1}^{T}\left(aP_{DG\_out}^2(t) + bP_{DG\_out}(t) + c\right) \quad (2)$$

where $P_{DG\_out}(t)$ represents DG active power output (kWh); a / b / c represent appropriate DG cost coefficients; T represents the 24h dispatch operation. The efficiency of DG can be computed according to Eq. (3) [34]:

$$\eta_{DG} = \frac{3.6\rho_{gen}}{\left(\alpha + \beta\rho_{gen}\right)LHV_{diesel}} \quad (3)$$

where α and β represent the cost coefficients; LHV_{diesel} represents lower heating value of diesel; ρ_{gen} represents DG relative output, defined as the ratio of electrical output to the rated capacity of the DG.

2.2.1. Proposed Minimum Operation Efficiency of DG

The Quasi-Newton optimization method in [35] is applied into Taylor's series expansion of Eq. (3) in order to determine the minimum operation efficiency of DG as follow:

$$f(\eta) = f(\eta_{DG}) + f'(\eta_{DG})(\eta - \eta_{DG}) + \frac{1}{2}f''(\eta_{DG})(\eta - \eta_{DG})^2 \quad (4)$$

Eq. (5) is obtained by setting the derivative of Eq. (4) to zero:

$$f'(\eta) = f'(\eta_{DG}) + f''(\eta_{DG})(\eta - \eta_{DG}) = 0 \quad (5)$$

We obtain Eq. (6) by dividing Eq. (5) through by $f''(\eta_{DG})$ improved simplification as:

$$\frac{f'(\eta)}{f''(\eta_{DG})} = \frac{f'(\eta_{DG})}{f''(\eta_{DG})} + (\eta - \eta_{DG}) \quad (6)$$

The Quasi-Newton convergence is further applied to obtain the minimum efficiency of DG in Eq. (7):

$$\eta_{DG\_min} = \eta_{DG} - \frac{f'(\eta_{DG})}{f''(\eta_{DG})} \quad (7)$$

The $f'(\eta_{DG})$ and $f''(\eta_{DG})$ are derived by applying quotient rule in Eq. (3), as given in Eq. (8) and (9) respectively:

$$f'(\eta_{DG}) = \frac{3.6\alpha LHV_{diesel}}{\left[\left(\alpha + \beta\rho_{gen}\right)LHV_{diesel}\right]^2} \quad (8)$$

$$f''(\eta_{DG}) = \frac{-7.2\alpha\beta LHV_{diesel}}{\left[\left(\alpha + \beta\rho_{gen}\right)LHV_{diesel}\right]^3} \quad (9)$$

Eq. (10) is then obtained by substituting Eq. (8) and Eq. (9) into Eq. (7) as:

$$Thus,\ \eta_{DG\_min} = \eta_{DG} + \frac{\left(\alpha + \beta\rho_{gen}\right)LHV_{diesel}}{2\beta} \quad (10)$$

where η_{DG} and $\eta_{DG\_\min}$ represent an approximate and minimum operation efficiency solution of DG respectively. The analysis was carried out using "*fminbnd", an* unconstrained optimization toolbox in MATLAB simulation and the minimum operation efficiency of the DG was found to be 30.00001%. Thus, the 30% minimum operational efficiency was then adopted in the dispatch operation.

2.3 Battery Energy Storage System (BESS)

The BESS consists of several series-parallel connected electrochemical cells capable to store required energy and it is measured in Ampere-hour (Ah). The BESS can be designed to cover the peak load demand especially during the non-viability of the RESs [36][37]. Thus, the higher the required voltage, the higher the number of cells connected in series and hence, the higher the investment and replacement costs.

In the proposed decentralized hybrid power system, the BESS is utilized as a primary backup to absorb excess energy produced by the PV and/or DG. The conserved energy is then dissipated to the load during low PV output. The state of charge is a performance index of the BESS which can be expressed in discrete time as follows [12]:

$$SOC(t) = SOC(t-1) + \eta_C \sum_{t=1}^{T} P_C(t) - \eta_D \sum_{t=1}^{T} P_D(t) \quad (11)$$

where $P_C(t)$ and $P_D(t)$ represent controllable charge and discharge power respectively; η_C and η_D represent efficiency of charge and discharge efficiency respectively. The dynamics of the BESS is expressed in relation to its initial state, as in Eq. (12):

$$SOC(t) = SOC(0) + \eta_C \sum_{t=1}^{T} \left(P_{PV}(t) + P_{DG}(t)\right) - \eta_D \sum_{t=1}^{T} \left(P_D(t)\right) \quad (12)$$

where $P_{PV}(t)$ and $P_{DG}(t)$ represent the variable active power flow from PV modules and DG respectively. The state of charge of the BESS is constrained within its boundary limits as:

$$SOC^{min}(t) \le SOC(t) \le SOC^{max} \quad (13)$$

The minimum state of charge is given as follows:

$$SOC^{min}(t) = (1 - DOD) SOC^{max} \quad (14)$$

where *DOD* represents the depth of discharge. It must be noted that the absorption and dissipation of power into and out of the BESS does occur simultaneously.

3. The Energy Optimization Models

This section presents two mathematical optimization formulations of the dispatch problem which include: MINLP and proposed combined control strategy taking into consideration operational constraints as highlighted in the sub-sections that follow.

3.1 MINLP Optimization Method

In this paper, the mixed integer nonlinear programming optimization technique is explored in the dispatch operation using "*Intlinprog*", an optimization toolbox in *MATLAB simulation*. The generalized MINLP algorithm is formulated as [38]:

$$\min_{x} f^T(x) \ \text{Subject to}: \begin{cases} Ax \le b \\ c_{eq} x \le d_{eq} \\ A_{eq} = b_{eq} \\ lb \le x \le ub \\ x_i \in Z \\ x_j \in \{0,1\} \end{cases} \quad (15)$$

where Ax and A_{eq} are matrices; x, b, b_{eq}, lb and ub are vectors; *f(x),* $c_{eq}x$ and d_{eq} are non-linear functions while $f(x)$ is a function that returns a scalar.
In this study, the objective function is formulated as follows:

Minimize

$$C_f = P_f \sum_{t=1}^{T} \left(a P_{DG\_out}^2(t) + b P_{DG}\_out(t) + c \right) \quad (16)$$

where P_f represents the fuel price per litre.

Subject to the following operational constraints:

(a) Power Balance Constraint
The total power supplied by the PV, BESS, DG must be equal to the load demand at any specified time:

$$P_L(t) = P_{PV}(t) + P_{BESS}(t) + P_{DG}(t) \quad \forall t = 1...N \quad (17)$$

(b) PV Generation Constraints
The active power dispatched from the PV system must be between the lower and upper limits as expressed in Eq. (18):

$$0 \le P_{PV}(t) \le P_{PV}^{max}(t) \quad (18)$$

(c) DG Generation Constraints
The power supplied by the DG must be within the lower and upper boundary during the dispatch operation:

$$P_{DG}^{min} \le P_{DG}(t) \le P_{DG}^{rated} \quad (19)$$

(d) State of Charge Boundary Condition
The hourly SOC must be equal to the sum of power accepted into or discharged out of the BESS:

$$SOC^{min}(t) \le SOC(0) + \eta_C \sum_{t=1}^{T} P_C(t) - \eta_D \sum_{t=1}^{T} P_D(t) \le SOC^{max} \quad (20)$$

(e) Non-negativity Constraints

The active power supplied by the PV, DG, BESS must be each greater than or equal to zero as specified in Eq. (21):

$$\mathrm{P_{pv}(t),\ P_{DG}(t),\ P_L(t)} \in Z^+ \ge 0 \quad (21)$$

(f) *The discrete ON/OFF decision constraints*
The discretized control variables which represent the DG ON/OFF state is expressed as:

$$\delta(t) = \{1,0\} \quad (22)$$

where $\delta(t)$ is the decision variable that represents the ON (unity) or OFF (zero) state of the DG.

3.2 The *Proposed Combined Dispatch Strategy*

The multi-objective, nonlinear cost function which seeks minimize DG fuel consumption cost by the maximization of RES is formulated as:

Minimize

$$C_f = f_p \cdot \left[\sum_{t=1}^{T} \left(aP_{DG\_out}^2(t) + bP_{DG}\_out(t) + c \right) .\delta(t) .\eta_{DG} - \sum_{t=1}^{T} P_{PV}(\text{t}) - \sum_{t=1}^{T} P_{BESS}(\text{t}) \right] \quad (23)$$

where $\delta(t)$ and η_{DG} represents the binary control and operational efficiency of the DG respectively.

Subject to the following operational constraints:

(a) The power balance and state of charge boundary constraints as we have in Eq. (17) and Eq. (20) respectively.

(b) Variable PV Operational Constraint

The PV output power supplied to the load and charged into the BESS must be less than or equal to the PV generated power, as in:

$$0 \leq P_L(t) + P_{BESS}(t) \leq P_{pv}(t) \quad (24)$$

(c) *The discrete ON/OFF control*
The DG operation efficiency ranges between its minimum and rated efficiency as:

$$\eta_{DG}^{\min} \leq \eta_{DG} \leq \eta_{DG}^{rated} \quad (25)$$

3.2.1 Description of Power Management of the Combined Dispatch Strategy

The power management of the combined dispatch strategy is described as follows:

A. *Cycle charging strategy*: Excess power is charged into the BESS when the PV output exceeds load demand, provided that its maximum state of charge has not been reached. However, whenever the maximum SOC is reached and PV output power exceeds the demand, the PID feedback control system is triggered to dynamically regulate the PV output such that only required power is produced by the PV systems. The strategy operates in the following approach:

(i). *BESS discharging strategy*: If the BESS and the PV output power proves to be sufficient to meet the load, the PV supplies all its output power while BESS complement the PV system to supply the net load while DG is turned OFF.

(ii). *BESS charging strategy*: If the BESS is insufficient to meet the net load, the DG is turned ON, giving between its minimum and rated output power to the load while the excess is stored into the BESS (if any).

B. *Load following strategy*: Whenever the BESS and DG minimum output power prove to be insufficient to meet the load, the PV supplies its whole portion while the DG regulates its operation efficiency to supply the required netload. Thus, the BESS will neither be charged nor discharged. The flowchart of the proposed strategy is shown in Fig. 2.

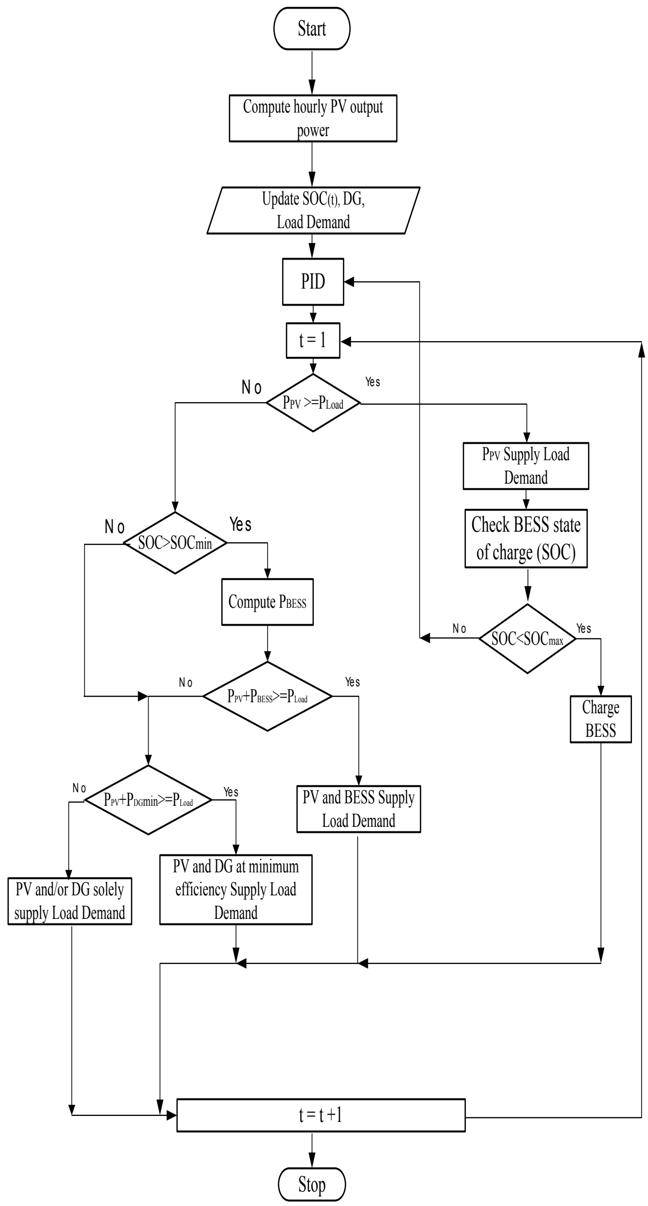


Fig. 2. Flowchart of combined dispatch operation of the decentralized hybrid power system.

3.2.2. Supply Description

The prioritized supply scenarios to meet the daily load demand are described as in Eq. (26):

$$P_{sup}(t) = \begin{cases} P_{PV}(t) \\ P_{BESS}(t) \\ P_{PV}(t) + P_{BESS}(t) \\ P_{DG}(t) + P_{BESS}(t) \\ P_{PV}(t) + P_{BESS}(t) + P_{DG}(t) \end{cases} \quad (26)$$

Therefore, the sum of the PV, DG and BESS output power during the dispatch operation must be less than or equal to the load demand as indicated in Eq. (27):

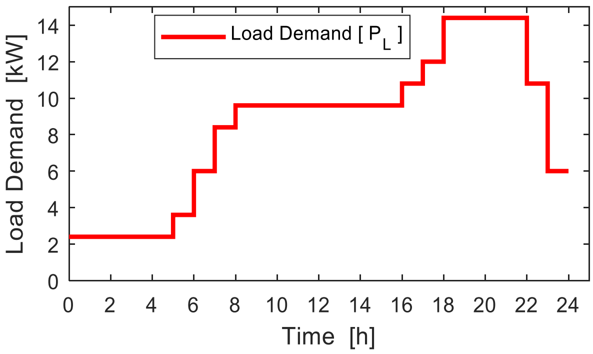
$$P_{pv}(t) + P_{DG}(t) + P_{BESS}(t) \geq P_L(t) \tag{27}$$

where $P_{sup}(t)$ represent the power supply by PV modules, BESS and DG.

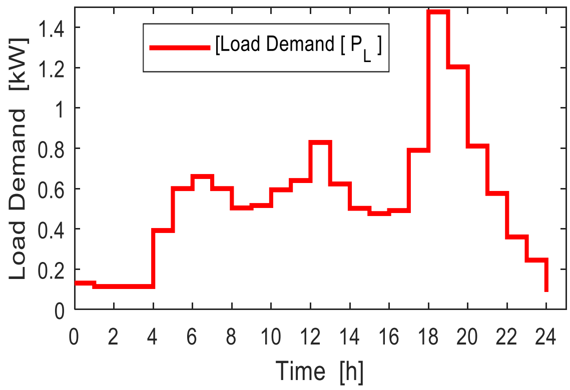
4. Case Studies

4.1. Daily Load Profiles

The dynamic single household and community daily load profiles used as case studies to analyze the benefits of the DHPS and contrasted to the DG single system are shown in Fig. 3a and 3b respectively [Homer Pro 3.11]. The two load profiles show a gradual increase from morning until the peak demand is reached in the evening and returned to its off-peak demand at midnight. The varying daily load profiles are then applied to the energy optimization models in section 3 to obtain real-time results.



a. Single household daily load demand



b. Community daily load demand

Fig. 3. Selected daily load profiles.

4.1. Model Parameters

The various system parameters utilized in the simulations are presented in Table 1.

Table 1. Model parameters and components capacity [5].

Parameter	Residential	Community
Sampling Time (minutes)	30	30
Nominal battery capacity (kWh)	2	12
BESS charge efficiency / DOD (%)	85 / 67	85 / 67
Minimum / maximum SOC (%)	30 / 90	30 / 90
N_{PVS} / N_{PPV}	4 / 1	60 / 1
Voc / Isc (V / A)	38.78 / 9.58	38.78 / 9.58
FF	0.7672	0.7672
DG rated capacity / Rated efficiency (*k*W / %)	1.8 / 90	16 / 90
DG minimum / Rated efficiency (%)	30 / 90	30 / 90
Diesel fuel price per litre ($/*l*)	1.2	1.2
a / b / c (*k*W/*l*)	0.0246 / 0.0815 / 0.433	0.0246 / 0.0815 / 0.433

4.2. Contribution Factor (DGCF)

The DG contribution factor is defined as the fraction of total power supplied by RES to the load as:

$$DGCF(\%) = \left[1 - \frac{\sum_{t=1}^{T} P_{PV}(t)}{\sum_{t=1}^{T} P_{DG}(t)} \right] \times 100\% \tag{28}$$

where $P_{DG}(t)$ and $P_{PV}(t)$ represent the daily total power produced by the DG and PV system respectively.

5. Results and Discussion

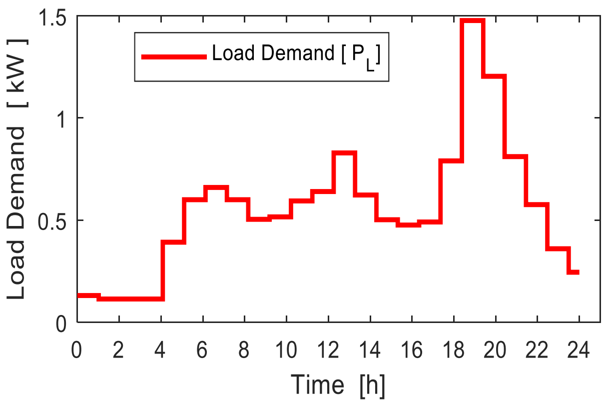
The simulation assessments of the two control strategies, which include MINLP and combined dispatch strategies are presented in this section. The results obtained are then contrasted to where the DG single system is utilized to supply the load demand.

5.1.MINLP Optimization Technique

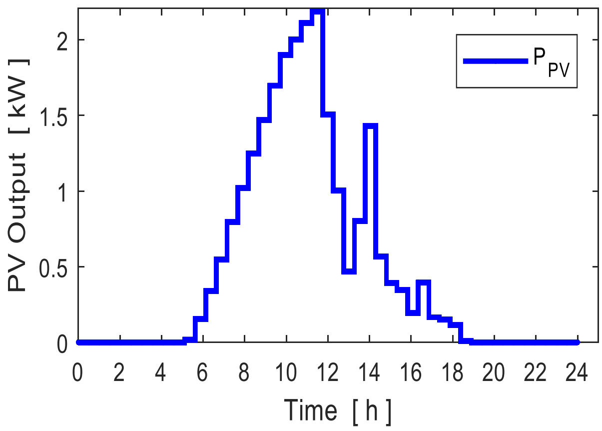
5.1.1.Case 1: Single household load

Figure 4 shows (a) single household load demand, (b) PV output power, (c) DG output power, (d) DG operation efficiency, (d) state of charge and (f) BESS power flow during a 24h operation. It is observed that the load demand is low in the morning while the PV output is zero due to the absence of solar radiation, therefore the DG is turned ON first at minimum efficiency, supplying a portion of its minimum output power to the load demand thus, minimizing its fuel consumption while simultaneously saving its excess power into the BESS as indicated in Fig. 4a, 4b and 4c.

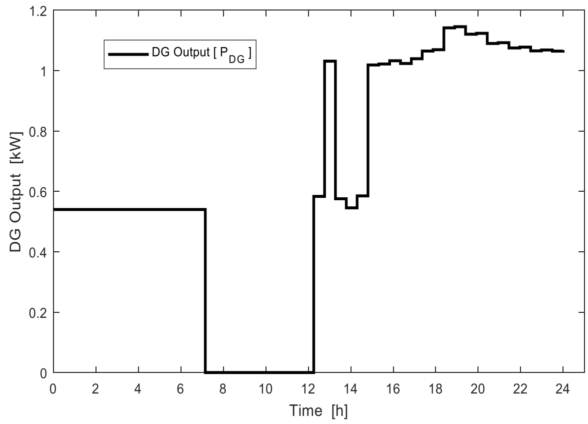
During the day, the load demand gradually increases and mainly supplied by the PV output power with its excess power being charged into the BESS as shown in Fig. 4b. The PV output power generated during the day satisfactorily covers the varying load demand while the surplus is absorbed into the BESS. Between 12h30–2400, the PV output is insufficient to meet the flexible load due to varying weather conditions. Thus, the DG is turned ON to complements the net load while the BESS compensates for the net load. At night, both DG and energy saved into the BESS during the day are utilized to serve the load as shown in Fig. 4c and 4e thus, minimizing DG fuel consumption. Figure 4f presents the downward and upward steps which represent power flow into (charging process) and out (discharging process) of the BESS respectively. The SOC constraint ensures that the absorption and dissipation power lies within a specified minimum and maximum range as shown in Fig. 4f. In any case during which the DG is turned ON, its operation efficiency ranges between the set minimum and rated efficiency regardless of the load demand as shown in the Fig. 4d. It is observed that the DG was OFF for a period of 5 hours with a DGCF of 36.21% to the load demand and the BESS (being part of the load). In this technique, the DG operational efficiency constraint leads to a significant saving in operational cost and normalized DG ON/OFF control.



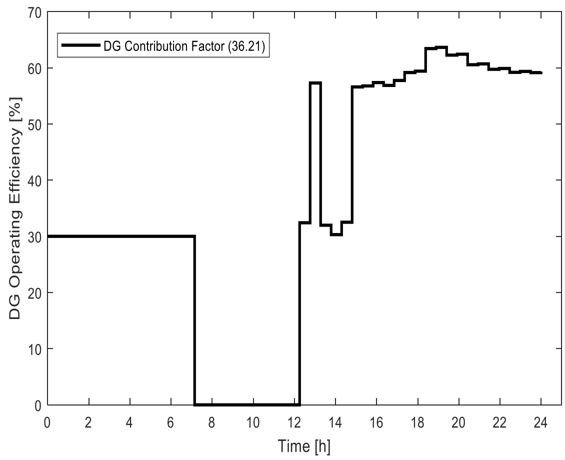
a. Single household load demand



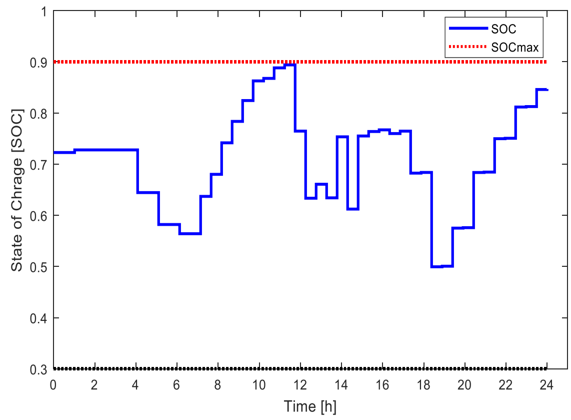
b. PV output power



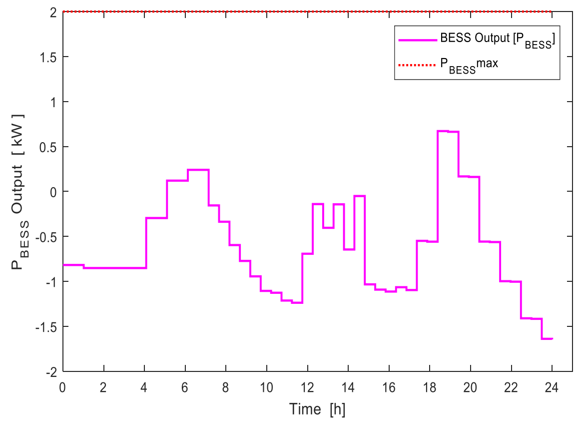
c. The DG power output



d. Operating efficiency of DG



e. The state of charge of the BESS



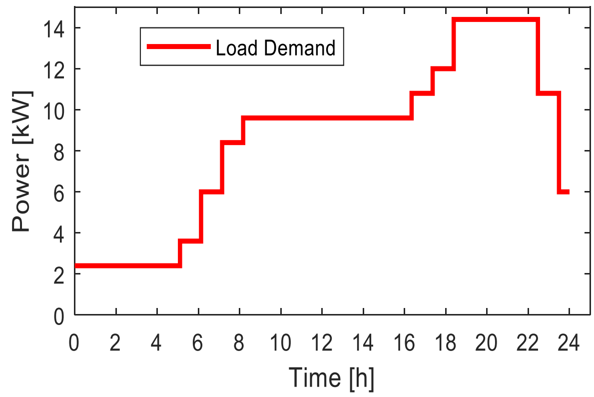
f. The BESS flow of power

Fig. 4. (a) Single household daily load demand, (b) PV output, (c) DG output power, (d) DG operation Efficiency, (e) state of charge and (f) BESS power flow during the 24h dispatch operation.

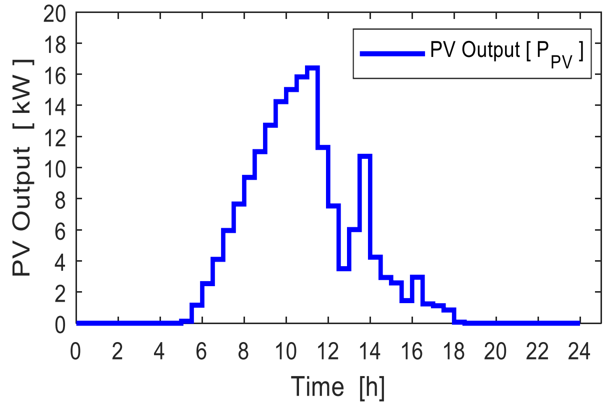
5.1.2.Case 2: The community load

Figure 5 presents (a) community load profile, (b) PV output power, (c) DG output power, (d) DG operation efficiency, (e) state of charge and (f) BESS power flow during a 24h operation. The community load profile is low in the morning, successively increases and becomes flat during the day, and attains its peak in the evening as depicted in Fig. 5a. In the morning, the DG supplies the load while its excess is being charged into the BESS. In the daytime, the PV system supplies the load while consecutively charges the surplus energy into the BESS as depicted in Fig. 5c, 5e and 5f. As the load rises in the evening through the night, the combined PV and BESS output power are insufficient to meet the load demand. Therefore, the DG is used to supply the net load. The DG is operated for about 21 hours while its operation efficiency varies within the specified limits during the dispatch operation as depicted in Fig. 5c and 5d, thus minimizing fuel consumption cost.

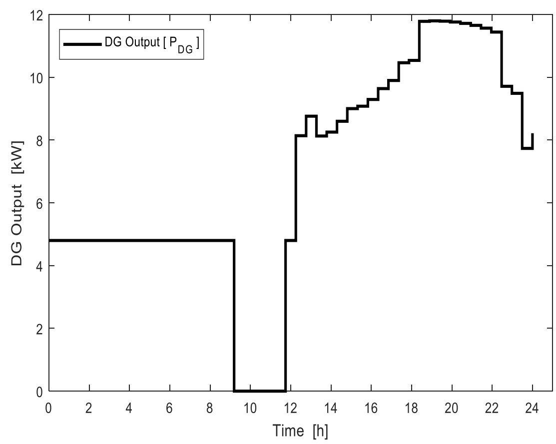
However, the DG's ON-duration is determined by the size of the BESS capacity, DG manufacturer's specification, number and ratings of selected PV modules. Therefore, a high BESS capacity can reduce the DG's ON-duration as well as minimize the DG fuel consumption cost. Nonetheless, this can increase the investment cost of the DHPS. Therefore, an optimal dispatch technique which optimizes the system components and minimizes the excessive DG ON/OFF control must be considered.



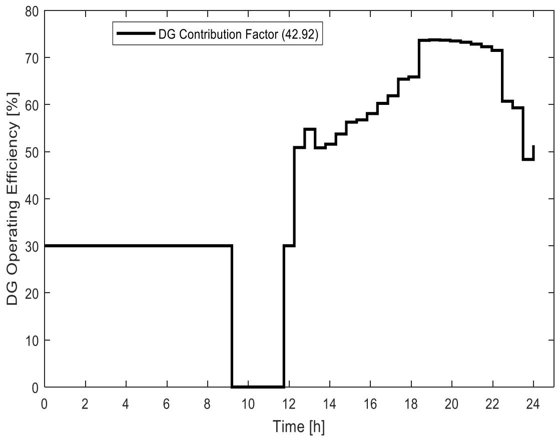
a. The single household load demand



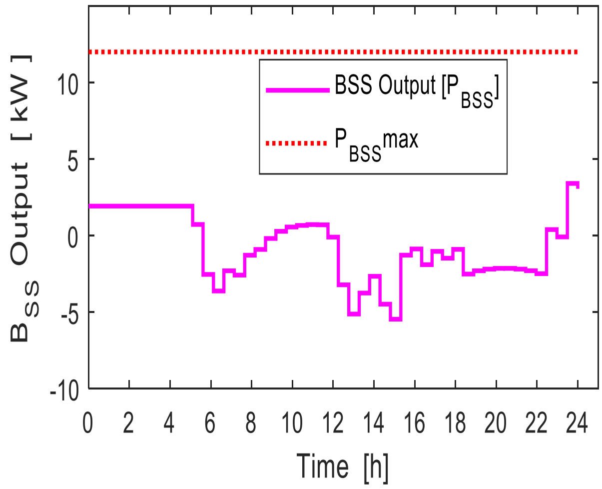
b. PV output power



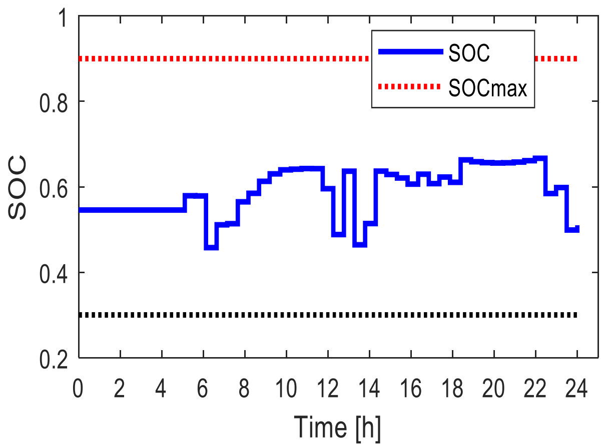
c. The DG power output



d. Operating efficiency of DG



f. The BESS flow of power



e. The state of charge of the BESS

Figure 5. (a) community daily load demand, (b) PV output, (c) DG output power, (d) DG operation Efficiency, (e) state of charge and (f) BESS power flow during the 24h dispatch operation.

5.1.3. Daily operation costs analysis

Table 2 presents the daily cost analysis using both single residential and community load scenarios compared to the specified DG single system in the dispatch operation of DHPS. The simulation results show the cost benefits of setting minimum operation efficiency of DG as well as the assessment of non-linearity of the cost function to minimize daily operation costs. It can be observed that significant cost saving can be achieved by the implementation of economically viable dispatch strategy in DHPS.

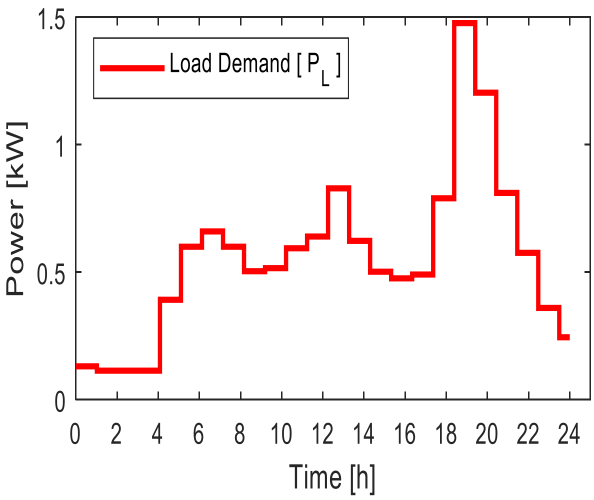
Table 2. Analysis of Daily Operation Costs (MINLP).

	Single Household Load			Community Load		
	Consumption (L)	Cost ($)	DGCF (%)	Consumption (L)	Cost ($)	DGCF (%)
DG Single System	12.70	15.24	100	101.58	121.90	100
PDB System	4.60	5.52	36.21	43.60	52.32	42.92
Savings	8.10	9.72	63.79	57.98	69.58	57.08

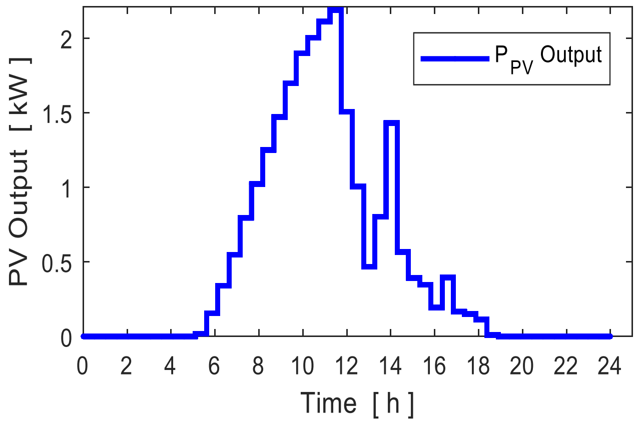
5.2.Combined Dispatch Strategy

5.2.1.Case 1: Single household load

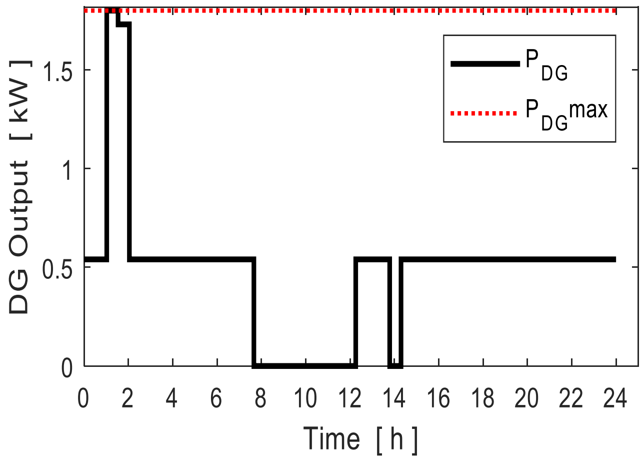
Figure 6 shows (a) single household load demand, (b) PV output power, (c) DG output power, (d) DG operation efficiency, (e) state of charge of the BESS and (f) BESS power flow during a 24h operation. Figure 6a indicates that the load demand is low in the morning, moderate during the daytime, relatively high in the evening and becomes low at night. In the morning, the DG supplies between its minimum and rated power for about 7:30hours while the surplus power is charged into the BESS for future consumption. At night, the DG is operated at minimum efficiency at relatively peak load while the BESS supply the net load. The stored energy of the BESS at maximum PV output and at other times when the PV output exceeds demand is discharged to service the net load in the night when the demand is relatively high. It can be observed that the DG is not operated upon, for a period of 6 hours during which the PV is sufficient to meet the load demand and thus, highly reduces DG fuel consumption. As a result of the minimum operation efficiency of the DG as well as its non-participation in power contribution to the load for prolonged hours, the total DG contribution factor is 26.59% of the entire load demand throughout the day as indicated in Fig. 6d and thus, significantly reduce operating costs. It is further observed that the excessive ON/OFF control coupled with unstable DG operation efficiency employed in previous works has been drastically minimized. The state of charge of the BESS is within the allowable limits during its charging and discharging process as represented in Fig. 6e and the power flow into and out of the BESS is depicted in Fig. 6f, with the downward and upward steps representing the charging process and discharging process respectively. The DG's ON-duration coupled with the number of ON/OFF cycles is determined by the size of the BESS capacity as well as the manufacturer rating and the number of the PV modules employed.



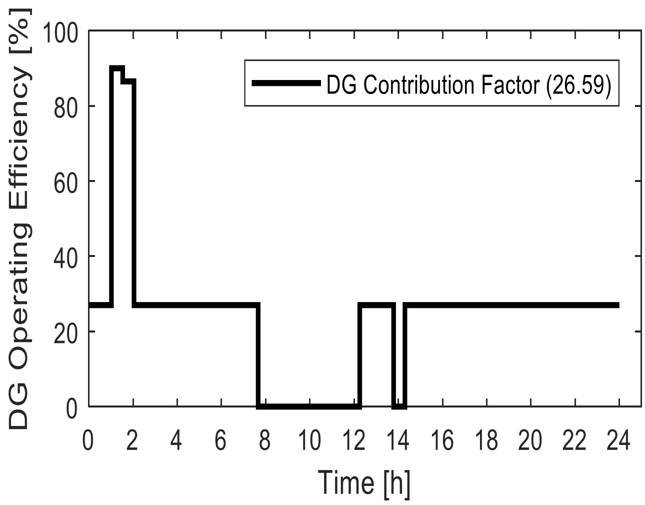
a. Single household load demand



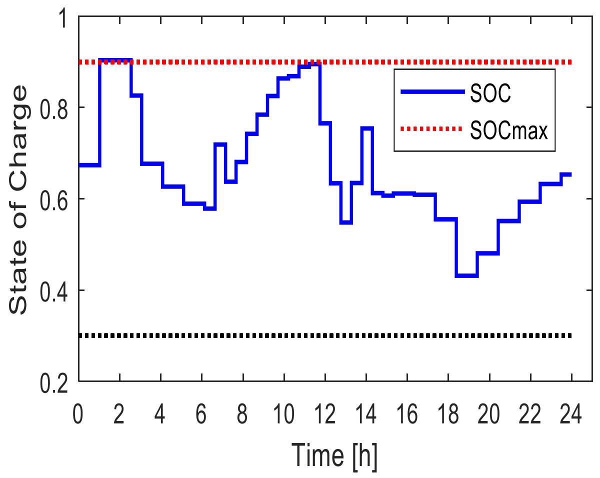
b. PV output power



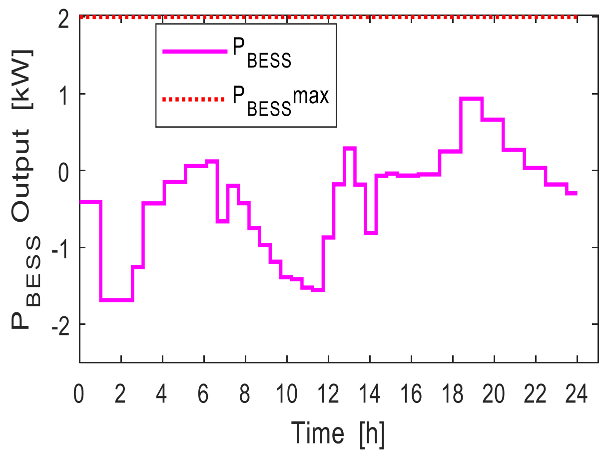
c. The DG power output



d. Operating efficiency of DG



e. The state of charge



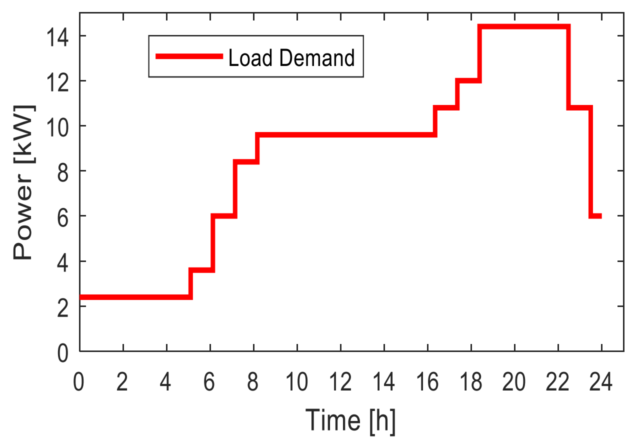
e. The BESS power flow

Fig. 6. (a) single household load demand, (b) PV output, (c) DG output power, (d) DG operation Efficiency, (e) state of charge and (f) BESS power flow during the 24h dispatch operation.

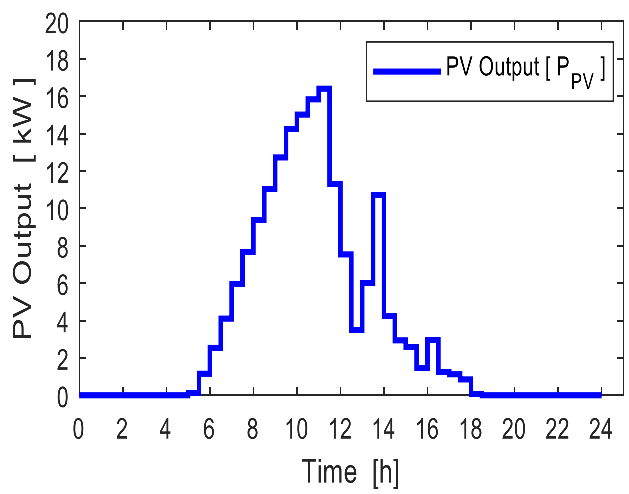
5.2.2.Case 2: Community Load

Figure 7 shows (a) community load demand, (b) PV output power, (c) DG output power, (d) DG operation efficiency, (e) state of charge and (f) BESS power flow during a 24–h operation. In Fig. 7a, the community load profile is also low in the morning, successively increases and becomes flat during the day and finally attains its peak demand in the evening. In the morning, the load demand is obviously lower than the minimum output power of the DG. In order to achieve an acceptable load factor, the DG is constrained to operate at minimum operational efficiency, giving a proportion of its output power to the load and simultaneously charging the BESS with its excess energy and thus, maintaining power balance. During the day, the energy produced by the PV is greater than the load demand hence, the DG is turned OFF state for 9 hours duration as shown in Fig. 7b and 7c. Therefore, the PV supplies the load and the excess energy is also charged into the BESS. The sufficient PV output power generated is responsible for the long DG OFF state as it contributes to a huge reduction in fuel consumption.

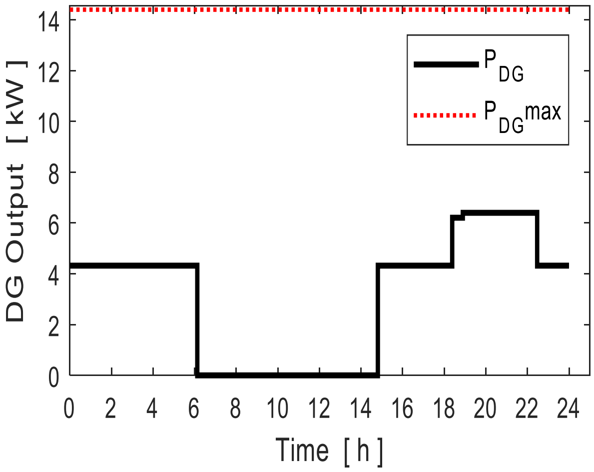
Conversely, the combined PV and BESS output is insufficient to satisfy demand in the evening, the DG is switched ON first at its minimum efficiency to supply demand. Thereafter, increased its operation efficiency meet the varying load demand as shown in Fig. 7c and 7d, in order to reliably meet the peak demand. The BESS complements the DG output power to satisfactorily meet the load demand. In this combined dispatch strategy, the fuel cost is greatly minimized and the DG operation efficiency is quite stable. The operational efficiency of the DG is shown in Fig. 7d, with the DG contribution factor of 21.75% of the load requirement as compared to the 42.92% for the community load in the MINLP dispatch strategy. The downward and upward steps of the BESS represent the charging and discharging process respectively as shown in Fig. 7f. Furthermore, the excessive DG ON/OFF control as well as the unstable DG operation efficiency has been drastically minimized.



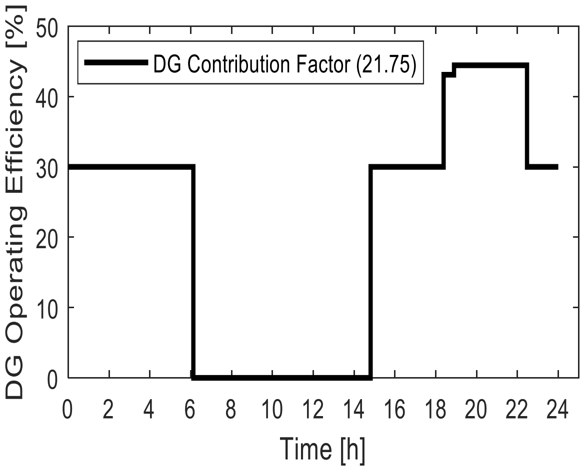
a. Daily Community load demand



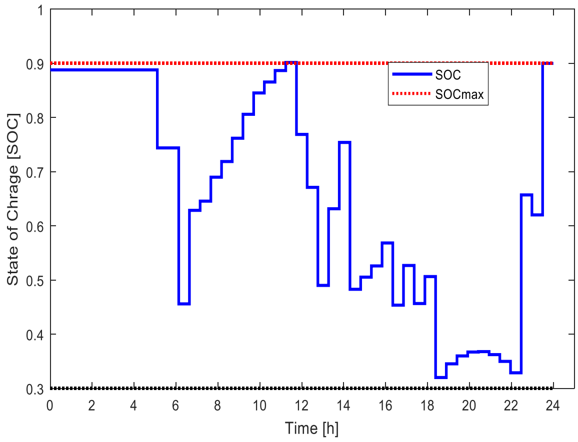
b. PV output power



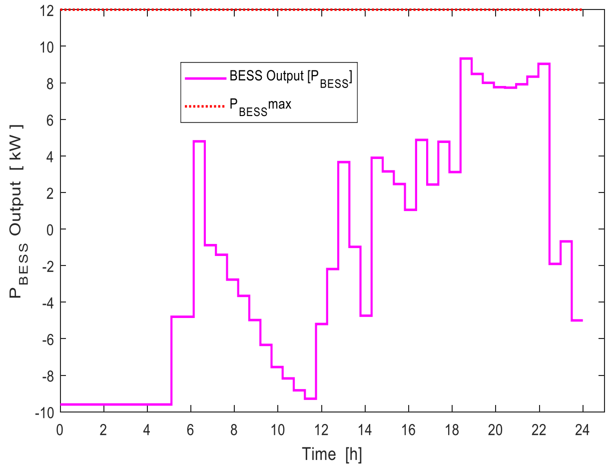
c. DG output power



d. DG operating efficiency



e. BESS state of charge



f. BESS power flow

Fig. 7. (a) community daily load demand, (b) PV output, (c) DG output power, (d) DG operation Efficiency, (e) state of charge and (f) BESS power flow during the 24h dispatch operation.

5.2.3. Daily Operation Cost Analysis

Table 3 presents the savings in fuel cost by comparing both DG single system with the hybrid power system for both single household and community scenarios. The simulation results obtained demonstrate the relevance of assessing the non-linearity of the DG fuel consumption cost as well as operating between its efficiency and rated efficiency in order to minimize daily operation costs using the combined dispatch strategy. The saving fuel cost depends on the DG ON/OFF duration and its operation efficiency, fuel consumption coefficient of the DG integrated, BESS operation settings (capacity, initial, minimum and maximum limits). Furthermore, the effectiveness of the developed combined dispatch strategy and constrained operating efficiency of the DG is demonstrated by the optimal control of the dispatch and higher BESS power supplied to the load, which ultimately leads to 73.41% and 78.28% reduction in the running cost of the hybrid system compared to 63.79% and 57.08% for the MINLP optimization technique, using the single household and community load profiles respectively.

Table 3. Analysis of Daily Operation Costs (Combined dispatch strategy).

	Single Household Load			Community Load		
	Consumption (L)	Cost ($)	DGCF (%)	Consumption (L)	Cost ($)	DGCF (%)
DG Single System	12.70	15.24	100	101.58	121.90	100
PDB System	3.38	4.06	26.59	22.09	26.51	21.75
Savings	9.32	11.18	73.41	79.49	95.39	78.28

6. Conclusion and Recommendation

In this paper, two energy dispatch strategies which include: MINLP and the proposed combined dispatch strategy have been considered in the optimization of hybrid power system to minimize daily operating cost of DHPS. The Minimum operation efficiency of DG was proposed using Quasi-Newton method in order to optimize operational and maintenance costs. The excessive DG ON/OFF control which characterized previous works has also been normalized. The results obtained show that the DHPS can significantly minimize daily fuel consumption cost as well as improve supply reliability when compared to DG-single system using both strategies. The result further showed that both the combined dispatch strategy and the MINLP optimization techniques brought about a significant daily operation cost reductions as well as reduce DG's operation duration compared to the DG single system. The efficacy of the combined dispatch strategy further demonstrated that an improvement of approximately 15.1% and 37.14% savings in daily operational cost can be achieved by using the dynamic household and community daily load demands respectively over the MINLP optimization technique. It is recommended that the system's life cycle cost is analyzed to determine the overall power system cost. In this studies, the dispatch techniques presented would immensely benefit system engineers in the integration of DHPS, as a solution to reduce over-dependence on the conventional power system, minimize operation cost and improve supply reliability.

Acknowledgment

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