Energy Management Strategies for PV/Diesel Hybrid Systems in Remote Areas: Effects of “Flexy-Energy” Strategy

Amidou Singho Boly *, Daniel Yamegueu *‡, Yézouma Coulibaly*

*Laboratoire Energies Renouvelables et Efficacité Energétique, Institut International d’Ingénierie de l’Eau et de l’Environnement (2iE), Rue de la science, 01 BP 594 Ouagadougou 01, Burkina Faso

(singho.boly@2ie-edu.org, dan.yamegueu@gmail.com, yezouma.coulibaly@2ie-edu.org)

‡ Corresponding Author: Rue de la science, 01 BP 594 Ouagadougou 01, Burkina Faso, Tel: +226 78 14 79 96, Fax: +226 25 49 20 01, daniel.yamegueu@2ie-edu.org or dan.yamegueu@gmail.com

Received: 19.11.2020 Accepted:22.12.2020

Abstract- Energy management strategies are crucial for the operation of hybrid energy systems. This paper focuses mainly on the implementation of a novel energy management strategy called Flexy-energy. A simulation tool was developed for power plants operating under this approach. The Operating range of load ratios (OpR) was used as an optimisation parameter to assess the performance of the strategy. The performance of the Flexy-energy strategy was then compared to the load following (LF) and cycle charging (CC) strategies, two strategies widely used in the management of hybrid energy systems. The Levelized Cost of Electricity (COE) is the main performance parameter considered in this paper. Two main outcomes have emerged from the present study. First, the Flexy-energy management strategy presents a lower COE than the LF and CC strategies. Second, the operating range of load ratios of diesel generators should be as large as possible for the Flexy-energy approach to lessen the COE. Indeed, under the Flexy-energy strategy, the scenario with an operating range of load ratios (OpR) within [25–100] has a COE of 9% lower than the one of the case with an OpR within [80–100].

Keywords- Rural electrification; Energy management strategy; Operating range of load ratios; Hybrid PV/Diesel system, Cost of electricity.

1. Introduction

Renewable energy sources are increasingly used to provide energy services to populations, especially in remote areas which are usually far from electric grids. Four main reasons can explain this trend. First, the competitiveness of renewable technologies [1], [2] as compared to conventional technologies. Second, the environmental challenges faced by stock energy sources. Indeed, the energy production impacts the environment and becomes a major aspect to be considered. Third, fossil fuels require larger and larger investments since their price increases, let alone their operating costs. The last reason includes the issue of scarcity of fossil fuel [3].

In Africa, solar technologies, especially photovoltaic, could help solve these energy challenges. The huge solar resource usually matches the energy demand of most urban and rural communities, with a global horizontal irradiation of about 5 $kWh.m^{-2}.day^{-1}$ in most countries [4].

However, the intermittency of some renewable energy resources like solar leads to concerns such as the stability or/and continuity of service. To deal with this issue, a combination of renewable energy sources with conventional sources or storage systems is often necessary [4]. This is called hybrid energy system. But these combinations lead to another problem, wich is the determination of the appropriate energy management strategy. Energy management strategy can be defined as a set of rules developed for the regulation of power flow in an energy system. They are often used with an optimisation algorithm to ensure that the optimal use and consequently a minimisation of the cost of energy are achieved.

Commonly, a hybrid system is associated with at least one objective function. This objective function may target an economic criterion (COE, operating costs, etc.)[5]–[7] or address a technical issue such as increasing photovoltaic penetration or reducing fuel consumption[8]. Besides, energy management strategies can be categorised into two families:

Conventional energy management strategies (CEMS): They rely on objective functions expressed in linear form. The CEMS can be used for both simple and complex systems. However, the performance of this type of strategy decreases when the system becomes more complex. This is the case for large-scale power plant, associations of several renewable sources, systems including battery storage, etc.

***Advanced energy management strategies (AEMS)*: ** They result from the use of intelligent optimisation techniques such as differential evolution, fuzzy logic, Genetic Algorithm (GA) or Neural Network. They mainly address complex hybrid energy systems with non-linear behaviours or large scale power plants.

Minimising the cost of energy (COE) is the most used criteria for assessing the performance of hybrid energy systems whether it is trough CEMS or AEMS.

In 2011, Rajkumar et al. [9] suggested a methodology for the sizing of a hybrid standalone power plant in Malaysia. The method took into consideration the loss of Power Supply Probability (LPSP) and was inspired by the neuro-fuzzy optimisation algorithm. A case study presented in their paper suggested an optimal configuration with a photovoltaic generator of 82kWp, a Wind generator of 28 kW and a battery system of 478 kWh capacity. They got a COE of $1.07/kWh.

The introduction of diesel generators in hybrid systems led to more attractive results. In 2013, Ismail et al. [10] suggested a techno-economic study of different scenarios of hybrid power plants. Their study aimed to look for the best configuration of power plant to meet a load profile using an energy management strategy based on linear programming. Three scenarios were analysed in this paper. The system including a photovoltaic generator of 16.43 kWp, a diesel generator of 7.5kW and a battery bank of 44 kWh was the most attractive with a COE of $0.239/kWh.

In 2014 another economic analysis on a hybrid PV/diesel/battery system was carried out in Saudi Arabia by Ramli et al. [11]. In that study, a COE of $0.117/kWh was reached with a diesel generator set of 2.1 GW a photovoltaic generator of 1.1 GW and battery storage of 186.96 MWh. This low COE was partly due to the accessibility and low cost of fossil fuel in this part of the world.

In the hybrid energy systems (HES) literature, software packages have been widely used to study energy management approaches of these systems[12]–[15]. Homer Pro and Matlab are the references software in the HES field. Homer pro suggests some energy management approaches as standard strategies. These approaches include the load following (LF) and the cycle charging (CC) strategies. They are management strategies based on specific rules and are particularly well-known and used around the world [16]–[19].

A few authors have used these two strategies to develop new ones assumed to be more effective. In 2019, Aziz et al[20] proposed a new energy management strategy based on the combination of Load following and Cycle charging strategies. In their work, these authors compared the three above-mentioned strategies (LF, CC, and their combination) in various case studies in an Iraqi village. The newly developed approach led to a cost of $0.21/kWh, which was 4.8% lower than the standard LF and CC strategies.

In recent years a new trend is to address the systematic use of storage technologies in hybrid systems. To support this trend, TSAI et al. [21] carried out a comparative study between different system configurations in 2020. The study was carried out for the island of Taiwan and included the following four system configurations: Diesel generator alone ; PV/batteries; PV/diesel and PV/diesel/batteries. The two most suitable configurations in terms of COE were the PV/diesel, and the PV/diesel/batteries with respectively a COE of 0.3569/kWh and $0.3581/kWh. These results meant to show the possibility of obtaining lower COE without battery storage.

It would be unfair to go further and compare the various COE listed above. Indeed, each of the studies mentioned was carried out in a specific context (renewable availability, fuel prices, maintenance costs, etc.). However, the following ideas can be sustained:

- Diesel generators can reduce the COE of hybrid energy systems;
- Reducing or suppressing the storage can be effective for the COE reduction;
- In this last decade, the cost of power in hybrid PV/Diesel systems ranged from around $0.2/kWh to $0.36/kWh. The idea is to get it as low as possible to compete with the conventional power technologies in each country or region of the world.

A new approach of energy management in hybrid energy systems called *Flexy-energy* has been proposed by Azoumah et al. [22]. This concept is both an energy management strategy and a philosophy of power plant arrangement. Mainly dedicated to rural and peri-urban areas, this approach consists of a hybrid standalone renewable-based system with limited storage capacity for peak shaving strategy. A conventional generator is used in the hybrid plant to smooth the intermittency of renewable sources. The energy management methodology of Flexy-energy concept relies on linear programming used with dynamic lookup tables.

In the development process of *Flexy-Energy* approach, several studies were carried out. Yamegueu et al. [23] conducted various experiments on a prototype of a 9.2 kW diesel generator and a photovoltaic array of 2.85 kWp. It was realised from these experiments that the sizing of a hybrid PV/diesel system should bring the diesel generator to operate at its optimal range, which is around 70–80% of its nominal power. The study further noted that the diesel generator should be capable of satisfying the peak load to guarantee the continuity of service and stability of power of the system. In Yamegueu et al. [24], the authors presented an economic investigation with three different scenarios: diesel generators only, PV only and hybrid PV/diesel. This investigation showed the economic viability of the hybrid PV/Diesel system. Tsuanyo et al. [25]-[26] presented an approach for the design and optimisation of power plants operating under the flexy-energy concept.

The previous studies conducted on the *Flexy- energy* strategy aimed to minimise the fuel consumption by operating the diesel generators at high efficiency with a load ratio of around 80%. One of the major criteria that should also be considered is undoubtedly the renewable energy penetration in a country or a regional level as it is mentioned in [8], [27]. In fact, the maximisation of renewable energy penetration can positively impact the COE.

The aim of this paper is to consolidate the *Flexy-Energy* approach by:

- ➢ Introducing a new optimisation approach based on the Operating range of the load ratio (OpR). The OpR is defined as the operating range allowed to the diesel generators. It must allow the generators to operate freely between a minimum and maximum load ratio.
- ➢ Designing a simulation tool for Flexy-energy plants using Matlab and Homer pro software. This simulation tool aims to facilitate the implementation of the flexy-energy concept.
- ➢ Carrying out a comparative study on the performance of the flexy-energy concept as compared to two widely used strategies, namely Load Following (LF) and Cycle Charging (CC) strategies. This last point is achieved through a case study carried out on a pilot power plant located at the Burkina Faso village of Bilgo.

2. Theoretical analysis

2.1. Overview of the Flexy-energy approach

The specificity of the *Flexy-Energy* approach is summarised here after:

- ➢ The Topology is considered in a way that the energy generators are close as possible to the consumers; this is meant to reduce the expensive costs related to the transportation lines for electricity.
- ➢ Loads must be classified based on their importance into critical loads, secondary loads and deferrable loads.
- ➢ 'flexy-control' is a set of items including a programmable logic controller (PLC), sensors and actuators. The sensors collect the meteorological data and the state of load demand. Based on this information, a production configuration is chosen. The controller then sends the order to start production to the generators designated by the chosen configuration.
- ➢ Energy Storage System (ESS) is avoided or limited to peak shaving strategy in the *Flexy-Energy* approach. Two main reasons justify this choice: first, the investment cost of storage technology which could reach 40% of the investment costs in convetional photovoltaic plants [25]; second, the lack of policies for the management of batteries at the end of their lifespan in most of the African countries.

The *Flexy-energy* approach is implemented using three matrices. The first two matrices are used to store all feasible combinations for generators of the same technology (diesel, photovoltaic, or wind turbine). The third matrix is a crossover type. It aims to contain all the feasible combinations of generators (conventional and renewable) in the same power plant.

For the most general hybrid PV/Diesel power plants, the configuration may be described as follows:

n = number of diesel generators, with n>1. The diesel units are labelled DGi with their rated power bei<span id="zotero-drag"/>ng Pi. 'k' is the number of scenarios that can be implemented with the diesel generators.

m = number of photovoltaic arrays with m>1. The PV arrays are labelled PVi with their instantaneous power being Pci.'q' is the number of scenarios that can be achieved with the photovoltaic arrays.

The combination matrices are presented in Table 1 and Table 2, while the crossover matrix is presented in Table 3.

Table 1. Matrix for Diesel generator combinations

Diesel Generators	*Scenario* SD_1	...	*Scenario* SD_k
DG_1	1	...	1
⋮	⋮	...	⋮
⋮	⋮	...	⋮
DG_n	0	...	1
Total power available	P_1	...	$P_1 + \ldots P_n$

Table 2. Matrix for PV combinations

PV arrays	*Scenario* SP_1	...	*Scenario* SP_q
PV_1	1	...	0
⋮	⋮	...	⋮
⋮	⋮	...	⋮
PV_m	1	...	0
Total power available	$PC_1 + \ldots PC_m$	...	0

In the combination matrices (Tables 1 and 2), Scenario SP1 corresponds to the use of all the PV arrays and Scenario SD1 corresponds to the use of diesel generator DG1 alone.

Table 3. Crossover Matrix for PV combinations

	Scenario SD_1	...	*Scenario* SD_k
Scenario SP_1	*Load ratio* $(SD_1;SP_1)$	...	*Load ratio* $(SD_k;SP_1)$
⋮	⋮	...	⋮
⋮	⋮	...	⋮
Scenario SP_q	*Load ratio* $(SD_1;SP_q)$	...	*Load ratio* $(SD_k;SP_q)$

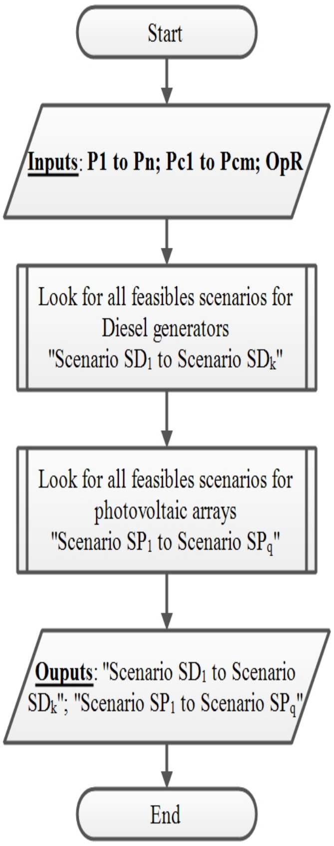
The cells of the crossover matrix in table 3 are filled by calculating the load ratio of the diesel generators involved in the concerned scenario. for example, the cell 1 of the crossover matrix refers to the diesel generators' scenario SD_1 and the photovoltaic scenario SP_1.

For each cell of the crossover matrix, the load ratio of the diesel generator set is calculated as in equation (1).

$$Load\ ratio = \left(\frac{Load_{demand} - P_{PV}}{P_{DG}}\right) \times 100 \qquad (1)$$

Where P_{PV} and P_{DG} are, respectively the total power available for the related photovoltaic scenario and the total power available with the diesel generator's scenario.

The Flexy-energy algorithm is displayed in Fig.1.



P1 to Pn being the rated power of the diesel generators

Pc1 to Pcm is the instataneous power of PV arrays

OpR Operating range of load ratios

Fig.1. *Flexy-Energy* test algorithm

The load ratios in the crossover matrix cells are used to select the right power sources to feed the load. Regarding to the chosen OpR, the required power sources are identified by looking out for the first cell of the crossover matrix with a value within the OpR. The check proceeds from the first to the last column, from, the first cell to the last cell.

The generators related to the first cell that's verifies the OpR criterion are selected to feed the loads. When it is not possible to fulfill the OpR criterion, all the generators of the power plant operate at their maximum capacity.

2.2. Overview of Load Following (LF) and Cycle Charging (CC) strategies

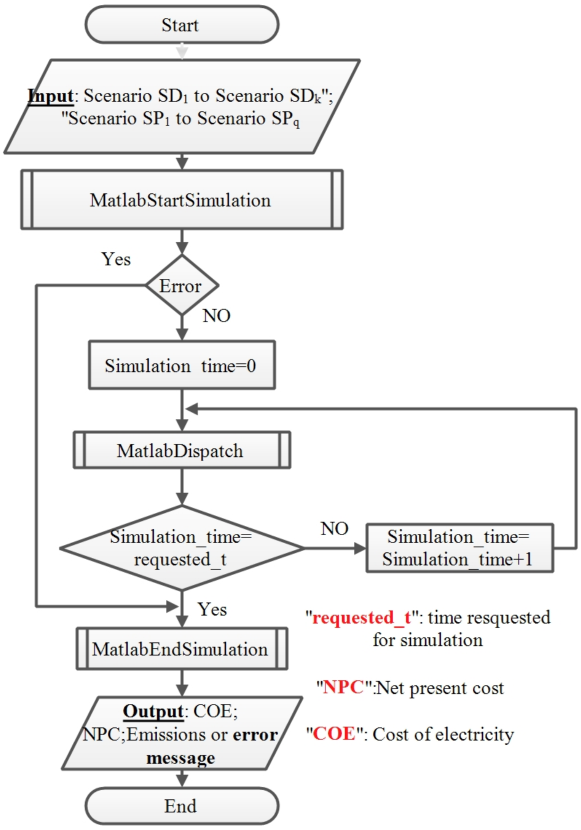
The Load following and the Cycle Charging strategies are standard energy management strategies of Homer pro. They are the commonly used strategies in hybrid energy systems.

Load following (LF) is a strategy in which, when a diesel generator is required, it supplies only the amount of energy necessary to satisfy the primary load (Renewable sources reload the batteries) [19]. Three situations composed this approach:

- Renewable power may be equal to the load demand. In this situation, the renewable energy satisfies the load while the batteries and diesel generators stay out of the load feeding.
- Renewable power can be more important than the load demand. In this case, the renewable output feeds the load and charges the batteries.
- Renewable power may be insufficient to feed the load. The batteries contribute then to meet the energy demand, respecting their minimum SOC. When the state of charge of the batteries is less than the minimum authorised, the generator starts to help meet the load demand.

The Cycle Charging (CC) strategy is different from the LF approach in the use of this threesome (diesel, batteries and renewable sources) system. Indeed, when the diesel generator is required, it supplies power at its maximum capacity, the energy excess goes then into the batteries [19].

The simulation algorithm of LF and CC (used in Homer pro software) is displayed in Fig. 2.



"**requested_t**": time resquested for simulation

"**NPC**":Net present cost

"**COE**": Cost of electricity

Fig.2. Simulation Algorithm of LF and CC strategies

2.3. Components modelling

The power generated by the PV is defined by equation (2)

$$P_{PV} = P_{Peak} \times D_f \left(\frac{G_T}{G_{STC}} \right) \left[1 + \alpha \left(T_{cell} - 25 \right) \right] \tag{2}$$

Where P_{PV} is the PV array output (kW). P_{Peak} is the peak power of the photovoltaic plant. D_f is the derating factor of the photovoltaic plant. G_T is the global solar irradiation (kW.m^{-2}). G_{STC} is the standard test condition irradiation (kW.m^{-2}). α is the temperature coefficient of photovoltaic panels. T_{cell} refers to the photovoltaic cell temperature (°Celsius).

The diesel generators are modelled by their fuel consumption as presented in the equation (3)

$$F = F_0 P_{DG} + F_1 P_{gen} \tag{3}$$

Where F is the hourly fuel consumption (L/h). F_0 is the fuel curve intercept coefficient or the no load fuel consumption (L.h^{-1}.kW^{-1}). P_{DG} refers to the rated power of the diesel generator (kW). F_1 is the fuel consumption curve slope (L.h^{-1}.kW^{-1}). P_{gen} is the power output from the diesel unit (kW).

2.4. Economic modelling

The economic modelling is achieved by the equations (4-6)

$$C_{annualised} = C_{NPC} \times CRF(i,n) \tag{4}$$

Where $C_{annualised}$ is the total annualised cost. C_{NPC} is the Net present cost value. i, is the discount rate. n is the project life time.

CRF is the capital recovery factor that may be determined by using equation (5)

$$CRF(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{5}$$

The Cost of Energy (COE) is determined by using equation (6). It is the cost of one kWh.

$$COE = \frac{C_{annualised}}{E} \tag{6}$$

Where $C_{annualised}$ is the total annualised cost of the power plant. E, is the total amount of electrical energy generated per year.

3. Case Study

The performance of the Flexy-energy management strategy is compared to the LF and CC strategies. Since energy storage is an important aspect of the LF and CC strategies, the simulations performed with these strategies were aiming to determine the optimal storage capacity and COE for the case study power plant. The performance of *Flexy-energy* management strategy was evaluated over seven OpR for the diesel generator sets. Thus, these seven OpR were the decision criterion for the choice of the generators to be used in the flexy-energy management strategy. For economic reasons, no storage capacity was considered in the flexy-energy approach simulations, thus bringing down the COE to a level where most people can afford energy.

The case study investigation was carried out on the village of Bilgo, Burkina Faso. The village is located in the commune of Pabre at about 30 km away from the capital Ouagadougou. The coordinates of the power plant are 12°32.0’N, 1 °40.8’W. The solar resource data were obtained from NASA’s surface Solar Energy data (see Fig.3).

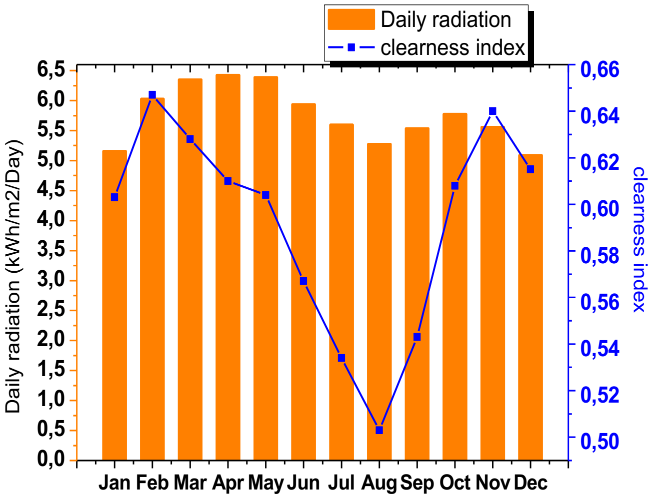


Fig.3. Solar radiation and clearness index on site

The clearness index is a ratio of radiation at the earth's surface to radiation on the top of the atmosphere. This ratio is comprised between zero and one.

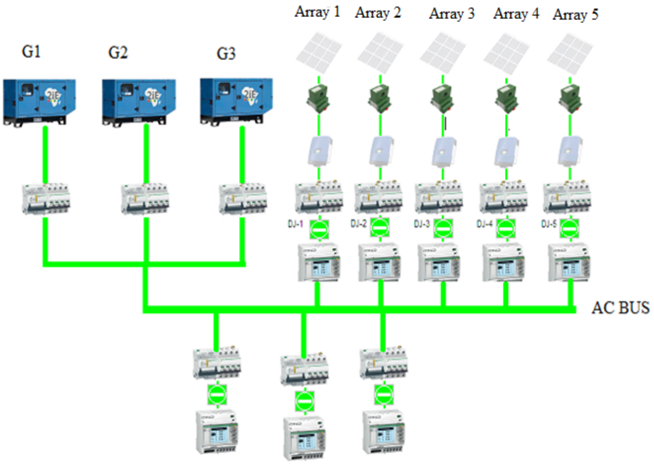


Fig.4 Schematic of the Bilgo’s power plant

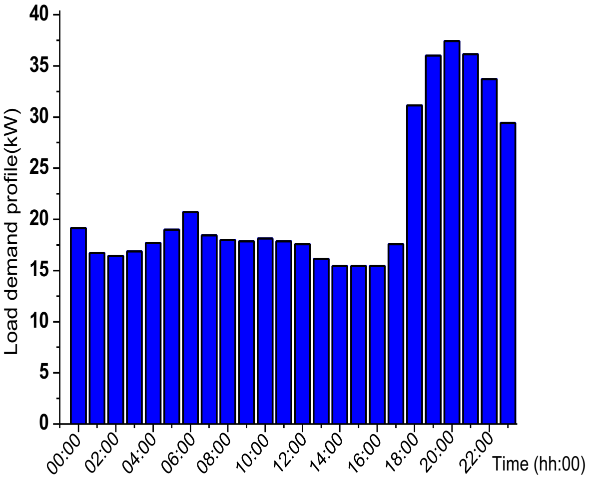


Fig.5. Daily load profile

The schematic of the case study power plant and the daily load profile are respectively displayed in Fig. 4 and Fig. 5. The daily load profile was obtained from an evaluation of the electrical needs of the village. No seasonal effect was considered for this study. However, a day to day variability and a time step variability of 10% have been considered. The techno-economic input parameters are specified in the Tables 4 and 5. The Bilgo power plant is composed especially of grid inverters and thus will only generate power when a power grid is available. For that reason, at least one diesel generator should run at any time to set the grid operating.

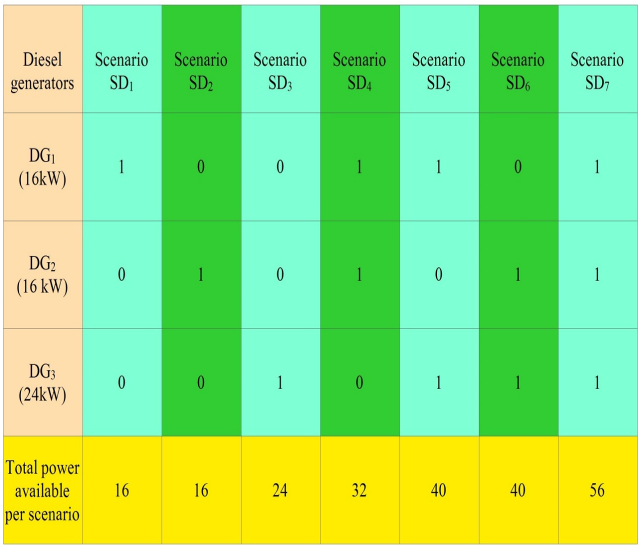
Table 1. Techno-economic input parameters

	Investments	**Operating and maintenance cost**	**Replacement cost**	**Life Time**
Diesel generator	1895 $/kW	0.030$/op. hour	1705 $/kW	15000 hours
Controller	59293.0 $	10 $/year	53363.70 $/kW	25 years
Photovoltaic array	1062.60 $/kW	10$/year	956.30/kW	25 years
Converters	1770.8 $/kW	0 $	1593.72 $/kW	15 years

Table 2. Other economic parameters

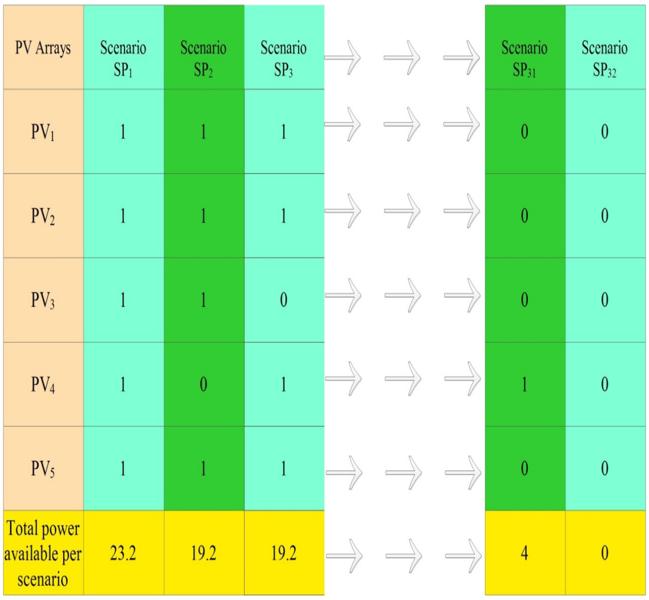
Fuel cost	0.96$/l
Discount rate	8%
Inflation rate	2%
Annual capacity shortage	0%
Project life time	25 years

For explanation purposes, the different types of matrix for the implementation of the *Flexy-energy* strategy are given in Figs. 6–8, using the Bilgo power plant configuration. This power plant is composed of three diesel generators (two of 16 kW and one of 24 kW) and a photovoltaic field of 30 kWp. The photovoltaic field is divided into five arrays, two arrays of 7.5 kWp and three arrays of 5 kWp. The nominal power of the inverters connected to these arrays are 7 kW and 5 kW for the PV arrays of 7.5 kWp and 5 kWp respectively.



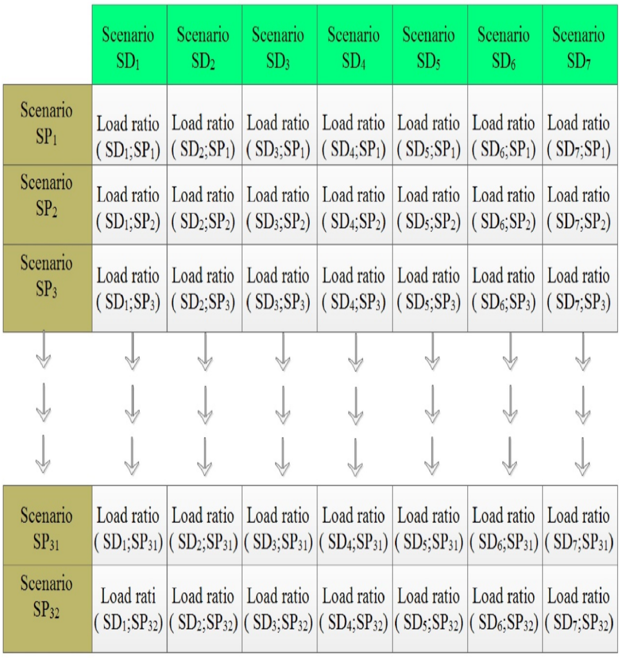
Diesel generators	Scenario SD_1	Scenario SD_2	Scenario SD_3	Scenario SD_4	Scenario SD_5	Scenario SD_6	Scenario SD_7
DG_1 (16kW)	1	0	0	1	1	0	1
DG_2 (16 kW)	0	1	0	1	0	1	1
DG_3 (24kW)	0	0	1	0	1	1	1
Total power available per scenario	16	16	24	32	40	40	56

Fig.6. Matrix for Diesel generator combinations in Bilgo power plant



PV Arrays	Scenario SP_1	Scenario SP_2	Scenario SP_3		Scenario SP_{31}	Scenario SP_{32}
PV_1	1	1	1	→ → →	0	0
PV_2	1	1	1	→ → →	0	0
PV_3	1	1	0	→ → →	0	0
PV_4	1	0	1	→ → →	1	0
PV_5	1	1	1	→ → →	0	0
Total power available per scenario	23.2	19.2	19.2	→ → →	4	0

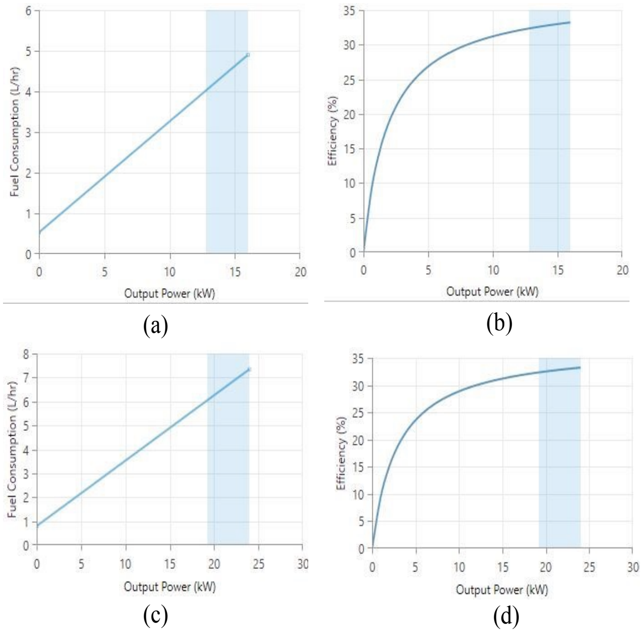
Fig. 7. Crossover matrix



	Scenario SD$_1$	Scenario SD$_2$	Scenario SD$_3$	Scenario SD$_4$	Scenario SD$_5$	Scenario SD$_6$	Scenario SD$_7$
Scenario SP$_1$	Load ratio (SD$_1$;SP$_1$)	Load ratio (SD$_2$;SP$_1$)	Load ratio (SD$_3$;SP$_1$)	Load ratio (SD$_4$;SP$_1$)	Load ratio (SD$_5$;SP$_1$)	Load ratio (SD$_6$;SP$_1$)	Load ratio (SD$_7$;SP$_1$)
Scenario SP$_2$	Load ratio (SD$_1$;SP$_2$)	Load ratio (SD$_2$;SP$_2$)	Load ratio (SD$_3$;SP$_2$)	Load ratio (SD$_4$;SP$_2$)	Load ratio (SD$_5$;SP$_2$)	Load ratio (SD$_6$;SP$_2$)	Load ratio (SD$_7$;SP$_2$)
Scenario SP$_3$	Load ratio (SD$_1$;SP$_3$)	Load ratio (SD$_2$;SP$_3$)	Load ratio (SD$_3$;SP$_3$)	Load ratio (SD$_4$;SP$_3$)	Load ratio (SD$_5$;SP$_3$)	Load ratio (SD$_6$;SP$_3$)	Load ratio (SD$_7$;SP$_3$)
Scenario SP$_{31}$	Load ratio (SD$_1$;SP$_{31}$)	Load ratio (SD$_2$;SP$_{31}$)	Load ratio (SD$_3$;SP$_{31}$)	Load ratio (SD$_4$;SP$_{31}$)	Load ratio (SD$_5$;SP$_{31}$)	Load ratio (SD$_6$;SP$_{31}$)	Load ratio (SD$_7$;SP$_{31}$)
Scenario SP$_{32}$	Load rati (SD$_1$;SP$_{32}$)	Load ratio (SD$_2$;SP$_{32}$)	Load ratio (SD$_3$;SP$_{32}$)	Load ratio (SD$_4$;SP$_{32}$)	Load ratio (SD$_5$;SP$_{32}$)	Load ratio (SD$_6$;SP$_{32}$)	Load ratio (SD$_7$;SP$_{32}$)

Fig.8. Matrix for PV combinations in Bilgo power plant

The diesel generators' technical information is given in Fig 9



(a) (b)

(c) (d)

Fig. 9. Diesel generators' technical information (a) Fuel flow DG1 and DG2 (b) EfficiencyDG1 and DG2 (c) Fuel flow DG3 (d) Efficiency DG3.

4. Results and Discussion

Simulation were carried out for seven scenarios under the flexy-energy management strategy. The simulated scenarios were based on different values of the OpR: [25–100]; [30–100]; [40–100]; [50–100]; [60–100]; [70–100]; [80–100]. Each diesel generator was allowed to run freely between the minimum and maximum load ratio in brackets.

Fig. 10 shows the cost of electricity for the LF and CC management strategies. For each storage capacity investigated, a sensitivity analysis was carried out on the converter size dedicated to the batteries. For this reason, one can notice that for one storage capacity, different COE are observed.

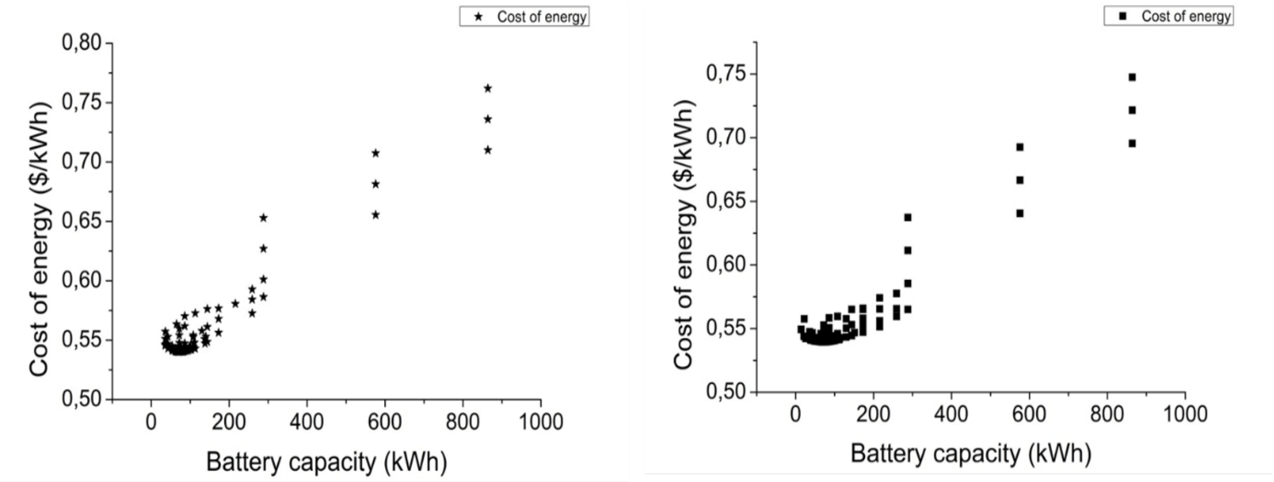
It can also be noticed from Fig.10 that, when the storage capacity increases the COE also increases. This observation is valid for both LF (Fig.10 a) and CC (Fig.10 b) strategies. One can notice that the optimal configuration for the LF was obtained with a storage capacity of 67 kWh with a COE of \$0.540/kWh while, the optimal configuration for the CC was obtained for a storage capacity of 69 kWh with a COE of \$0.539/kWh.

Fig. 11 presents the results of the seven scenarios used in the simulations with the flexy-energy approach. From that figure, one can notice that the cost of electricity increases when the OpR range is reduced. For instance, the lowest cost of electricity was observed with an OpR of [25–100], while the highest cost was obtained with an OpR of [80–100]. Indeed, the scenario with an Operating range of load ratios (OpR) of [25–100] has a COE 9% lower than the case with an OpR of [80–100]. This can be explained as, the wider the OpR, the lower the fuel consumption. Indeed, for a wide range of OpR, the solar contribution is higher, hence the participation of the diesel generators for energy generation is lowered.

When we compare the results obtained from the LF, the CC and the flexy-energy strategies, it appears that the flexy-energy strategy has the best performance in terms of COE. However, when the OpR is [80-100], the LF and CC strategies are more efficient than the flexy-energy approach. In fact, for this last case, the COE obtained was 0.544 \$/ kWh, which is higher than those of the other strategies.

From the results of the flexy-energy approach, one can argue that the optimal operation of a hybrid PV/diesel system (without storage) is not necessarily met when diesel generators operate in a range close to their optimal load ratio (75 to 80%). An investigation was thus conducted using the simulation results for two reference days. For each day, the responses of the power plant under the two OpR of [25–100] and [80–100] are displayed and analysed.

The results of January 1 are displayed in Figs. 12-13. The Load profile of that first day is presented in Fig. 12 a. During this day, the irradiance (Fig.12 b) was between 0 and 250 W/m^2 indicating a cloudy day.



(a)

(b)

Fig.10. COE (a) LF strategy; (b) CC strategy

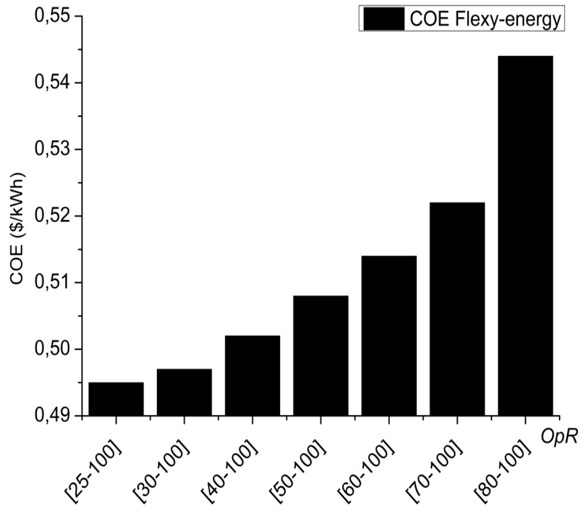


Fig. 11. COE with the Flexy-energy strategy

A comparison between Figs. 12 c and 12 d shows that the load sharing ratio in the scenarios [25–100] and [80–100] are similar, except for 8 am. Indeed, higher solar power integration can be seen in the scenario [25–100].

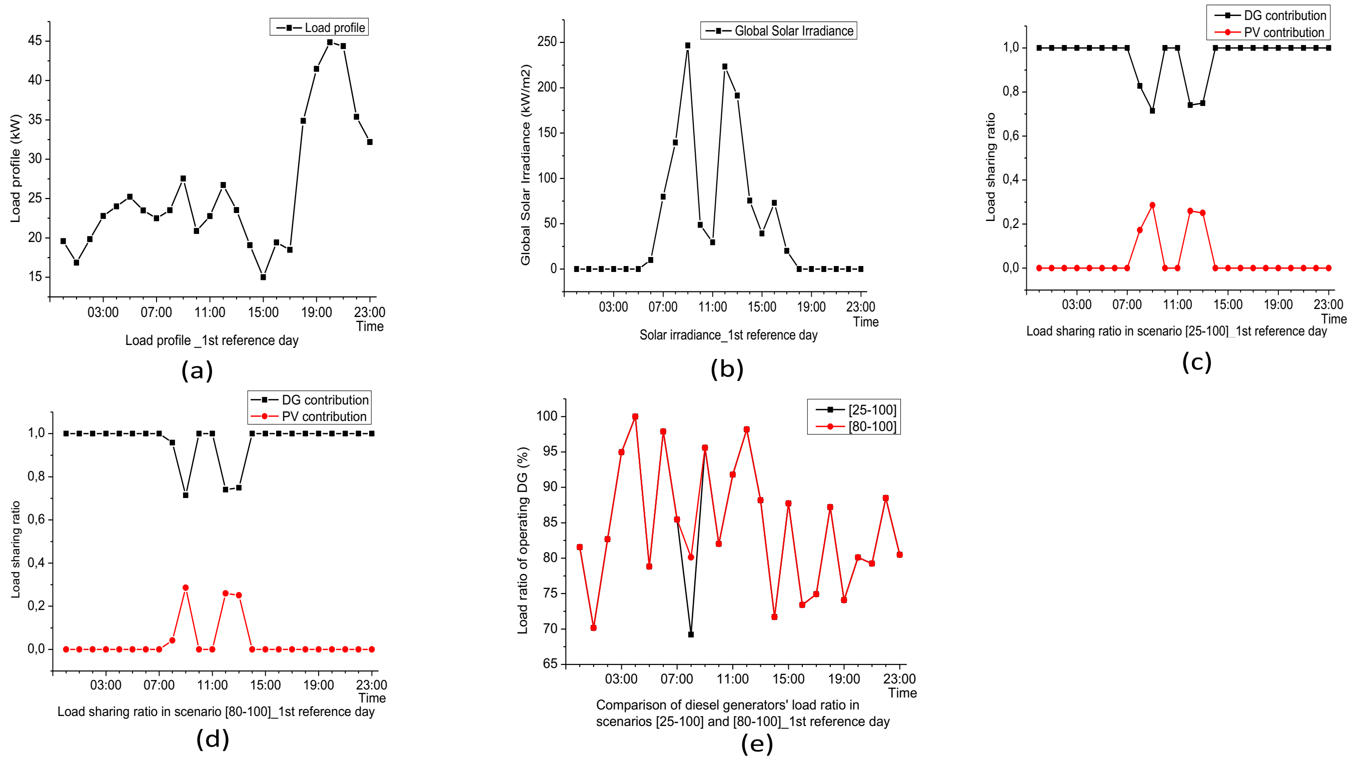
Fig.12 e shows that the diesel generators have the same load ratio in the two scenarios except at 8 am. This confirms the remarks made for the trends in Figs.12 c and 12 d.

The operating schedule of the PV and Diesel generators during the 1st reference day is presented for the cases [25–100] and [80–100] in Fig.13. This figure shows that, whatever the case, the same diesel generators are always used together at the same time. One can also notice that all the photovoltaic generators are used at the same times in both scenarios except at 8 am.

The results of the second day, January 3rd, are presented in Figs.14-15. During that day, the irradiance observed shows that it was a cloudless day. The related load profile is presented in Fig. 14 a.

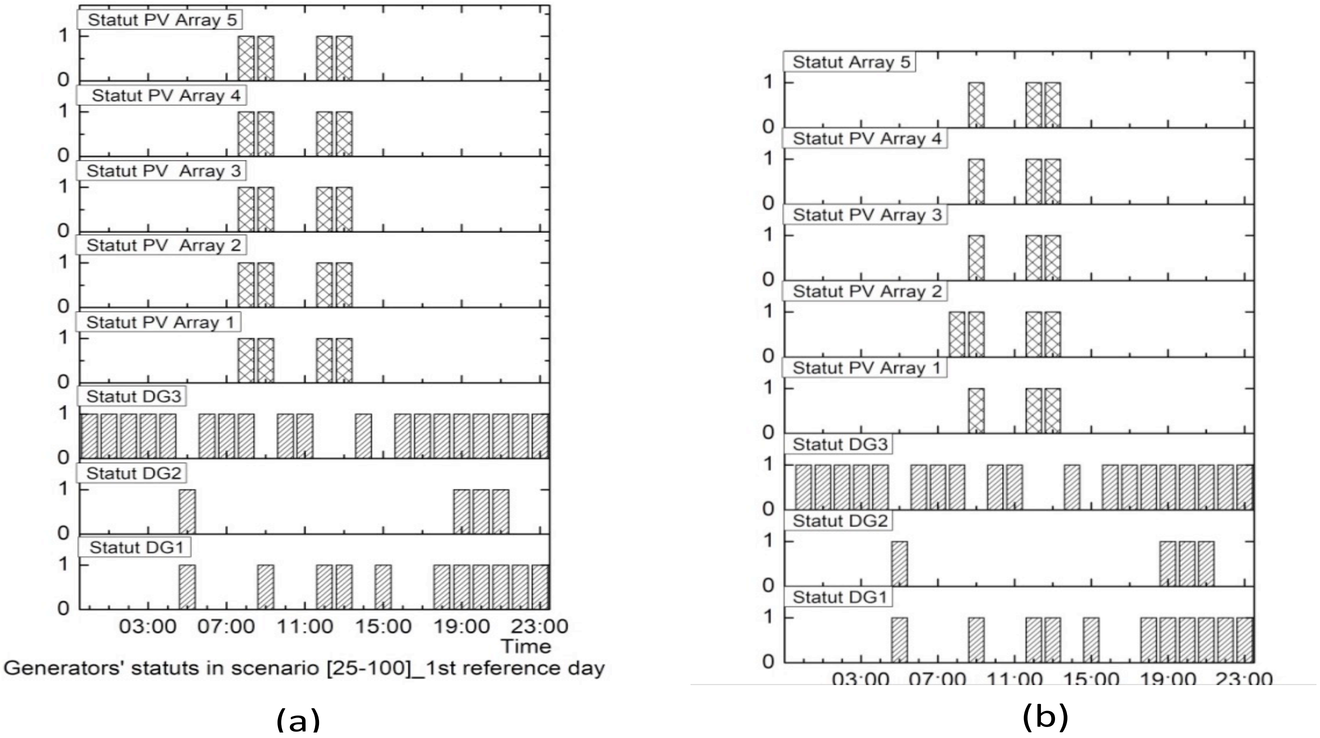
A comparison between trends in Figs.14 c and 14 d shows that the contribution of the diesel generators is much more significant in the scenario [80–100] than the scenario [25–100]. Moreover, Fig.14 d presents an energy excess at 1 pm. This excess is noticed for a load sharing ratio superior to one. The load ratios equal or superior to 1 can be explained by the fact that the OpR condition has not been fulfilled at this step. As stated previously, when it is not possible to fulfill the OpR criterion, all the generators of the power plant operate at their maximum capacity. Consequently an energy excess occurs and is dissipated as there is no deferrable loads in the case study. This operating choice was used to analyse the situations where the OpR running conditions are not respected. The energy excess in this scenario was less than 1%; consequently, one can deduce that the OpR condition is respected most of the time. The trend in Fig.14 e depicts that diesel generators operate at a lower load ratio in the scenario [25–100] when the solar resource is available.

It can be pointed out from Figs.15 a and 15 b that the diesel generators operate at the same time, except at 1p.m. for both simulation cases.



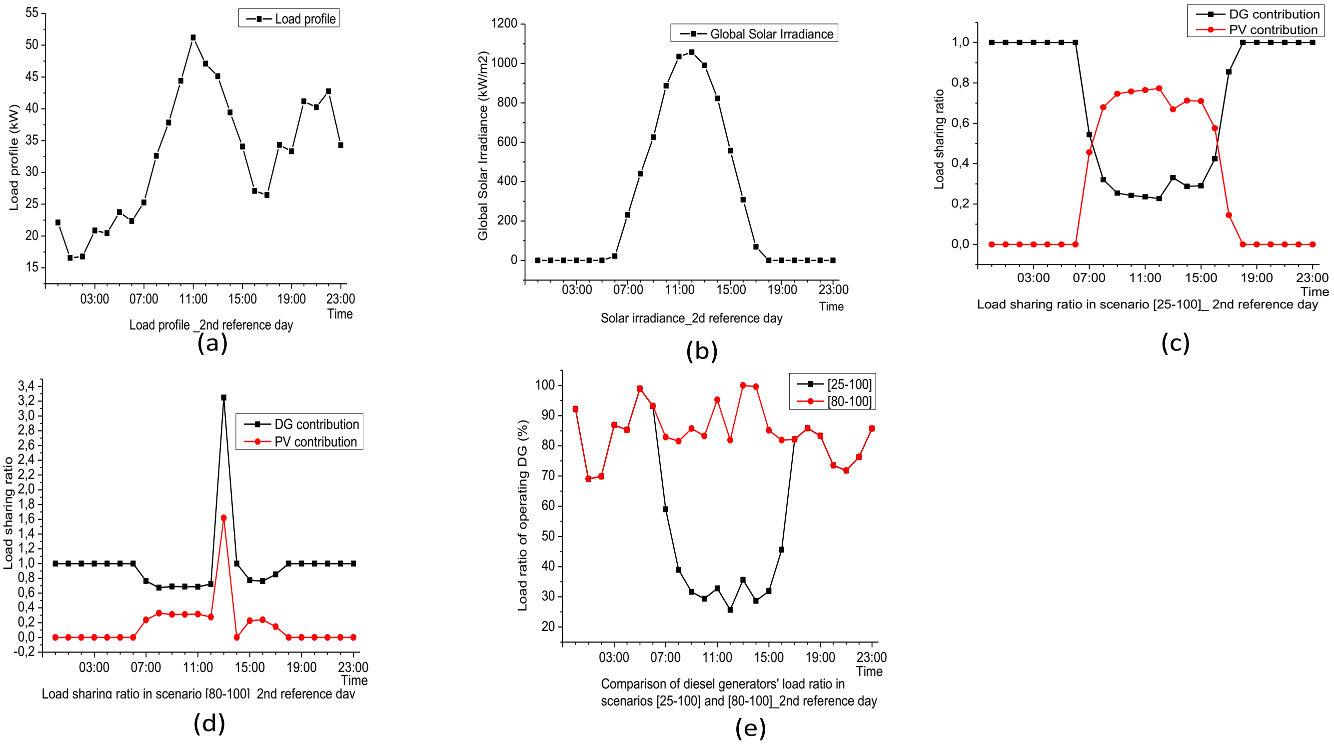
(a) (b) (c) (d) (e)

Fig. 12. Simulation inputs and results of January 1st (a) Load profile (b) Solar irradiance (c) Load sharing ratio of energy sources in scenario [25-100] (d) Load sharing ratio of energy sources in scenario [80-100] (e) Comparison of diesel generators' load ratio in scenarios [25-100] and [80-100]



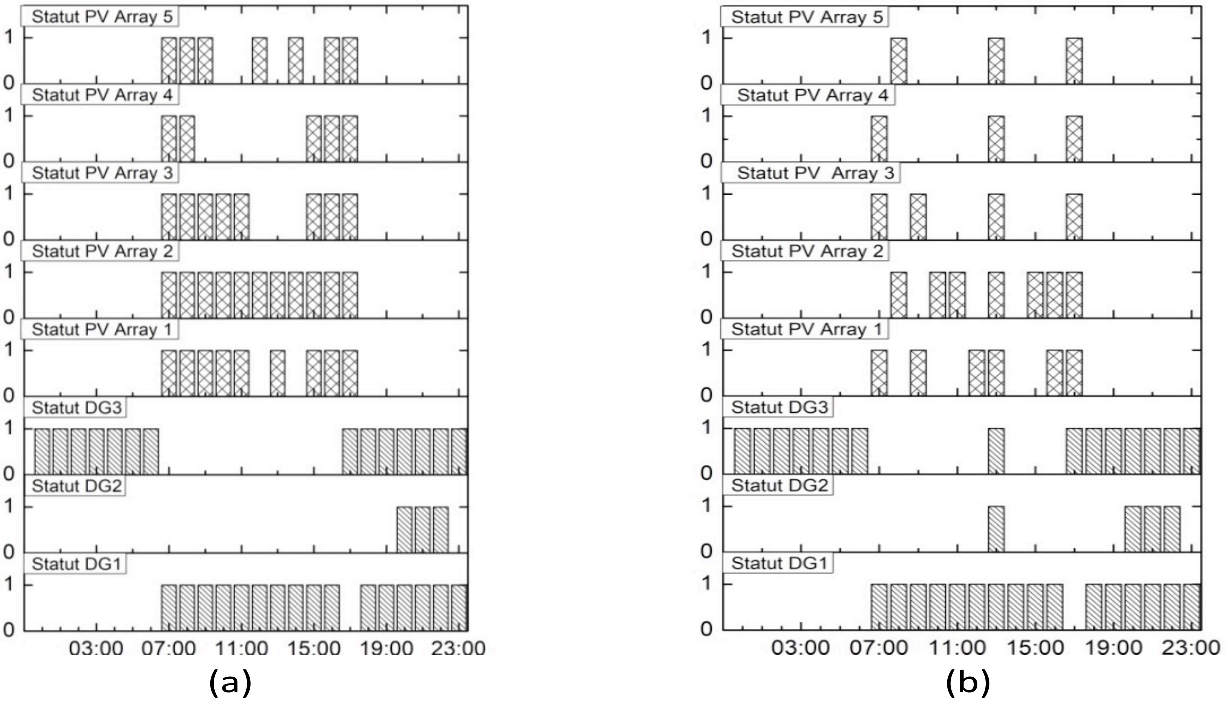
(a) (b)

Fig. 13. Generator’s status (a) scenario [25–100] (b) scenario [80–100]



(a) (b) (c) (d) (e)

Fig. 14. Simulation inputs and results of January 3rd as 2nd reference day (a) Load profile (b) Solar irradiance (c) Load sharing ratio of energy sources in the scenario [25–100] (d) Load sharing ratio of energy sources in the scenario [80–100] (e) Comparison of diesel generators' load ratio in scenarios [25–100] and [80–100]



(a) (b)

Fig. 15. Generator's status (a) scenario [25–100] (b) scenario [80–100]

From the analysis carried out based on the results of Figs.12-15, one can conclude that the scenario [25–100] allows greater integration of solar power than that of [80–100]. Besides, the number of generators in operation and their load ratios in the scenario [25–100], is less or equal to those in scenario [80–100]. Then, the best scenario in terms of the cost of electricity is the scenario with the largest operating range of load ratios [25–100].

The results show that in terms of COE, the optimal operation of a hybrid PV/diesel system without storage is not necessarily met when diesel generators operate in a range close to their optimum load ratio, around 80% of their nominal power. The results obtained in this paper can be supported by the study of *Evgenii Semshchikov et al*. [28]. In this study, the authors have demonstrated that low load diesel technology can increase renewable penetration and avoid expensive use of storage technology. Furthermore, A study conducted by *James Hamilton et al*. [29] has also lead to the same results. Indeed, the authors have explored a methodology for wind and solar PV integration, without storage. This approach has demonstrated the benefits of low load diesel operations. The authors have obtained by this approach a renewable energy integration higher than 50% and an investment ment reduction around 32%.

5. Conclusion

A new optimisation approach was introduced in this study and a simulation tool was developed for the flexy-energy management strategy, using Matlab and Homer pro software. A comparison with two other energy management strategies, namely Load Following (LF) and Cycle Charging (CC) was carried out using the case study of the power plant in the village of Bilgo, Burkina Faso. The simulations of the power plant under the three energy management strategies studied with sensitivity analysis on the Operating range of load ratios were performed. The Flexy energy management strategy has shown the best performance (in terms of COE) than LF and CC strategies. From the results of the study, it appears that the Operating range of load ratios is a significant criterion which influences the cost of electricity of the power plant. Generally, the optimal load ratio for a diesel generator is set around 80% of the rated power. In that case, even if the hourly fuel consumption is high, the specific consumption is always low. However, the lowest levelized cost of electricity was got for all the energy management strategies in the scenario with the Operating range of load ratios equal to [25–100] instead of [80–100] which is closer to the common recommended operating range for diesel generators. The Operating range of load ratios used in the flexy-energy approach should then be as broad as possible. We may then conclude that the optimal operation of diesel generators do not necessarily coincide with the optimal running of the hybrid power plant. These results introduce new issues that need to be addressed to ensure the reliability along with the cost-effectiveness of flexy-energy power plants. Thus, further studies are recommended to investigate the real impact of using a diesel generator at a low load ratio in flexy-energy power plants. One should also determine the minimum load ratio that a diesel generator can endure without affecting both the power quality and its lifetime.

Acknowledgements

The authors are grateful to DAAD (Deutscher Akademischer Austauschdienst) for the financial support of this study through the In region scholarship programme-2iE, funding program number 57313342.

References

[1] Adnan Z. Amin, “ How Renewable Energy Can Be Cost-Competitive”. https://www.un.org/en/chronicle/article/how-renewable-energy-can-be-cost-competitive. Accessed 02 March 2020.

[2] A. Shahid, “Smart Grid Integration of Renewable Energy Systems”, 7th International Conference on Renewable Energy Research and Applications (ICRERA), Paris, pp. 944-948, 14-17 October 2018.

[3] T. Covert, M. Greenstone, and C. R. Knittel, “Will We Ever Stop Using Fossil Fuels?”, Journal of Economic Perspectives, Volume 30, pp. 117-138, January 2016.

[4] Solar ressource map “Global Horizontal Irradiation”. https://solargis.com/maps-and-gis-data/download/world. Accessed 02 March 2020.

[5] L. Moretti, M. Astolfi, C. Vergara, E. Macchi, J. I. Pérez-Arriaga, and G. Manzolini, “A design and dispatch optimization algorithm based on mixed integer linear programming for rural electrification”, Applied Energy, vol. 233-234, pp. 1104-1121, January 2019.

[6] T. Wang, X. He, and T. Deng, “Neural networks for power management optimal strategy in hybrid microgrid”, Neural Computing and Application, vol. 31, pp. 2635-2647, July 2019.

[7] X. Jiang and C. Xiao, “Household Energy Demand Management Strategy Based on Operating Power by Genetic Algorithm”, IEEE Access, vol. 7, pp. 96414-96423, 12 July 2019.

[8] A. M. Dejamkhooy, M. Hamedi, H. Shayeghi, and S. J. SeyedShenava, “Fuel Consumption Reduction and Energy Management in Stand-Alone Hybrid Microgrid under Load Uncertainty and Demand Response by Linear Programming”, Journal of Operation and Automation in Power Engineering, vol.8, pp.273-281, February 2020.

[9] R. K. Rajkumar, V. K. Ramachandaramurthy, B. L. Yong, and D. B. Chia, “Techno-economical optimization of hybrid pv/wind/battery system using Neuro-Fuzzy”, Energy, vol. 36, pp. 5148-5153, August 2011.

[10] M. S. Ismail, M. Moghavvemi, and T. M. I. Mahlia, “Techno-economic analysis of an optimized photovoltaic and diesel generator hybrid power system for remote houses in a tropical climate”, Energy Conversion and Management, vol. 69, pp. 163-173, May 2013.

[11] M. A. M. Ramli, A. Hiendro, and H. R. E. H. Bouchekara, «Performance Analysis of Hybrid PV/Diesel Energy System in Western Region of Saudi Arabia», International Journal of Photoenergy, vol. 2014, pp. 1-10, 13 May 2014.

[12] L. Barote and C. Marinescu, “Li-Ion energy storage capacity estimation in residential applications with EV”, 8th International Conference on Renewable Energy Research and Applications (ICRERA), Brasov, pp. 326-330, 3-6 November 2019.

[13] N. E. Zakzouk, A. E. Dyasty, A. Ahmed, and S. M. El Safty, “Power Flow Control of a Standalone Photovoltaic-Fuel Cell-Battery Hybrid System”, in 2018 7th International Con-

ference on Renewable Energy Research and Applications (ICRERA), Paris, pp. 431-436, 14-17 October 2018.

[14] S. R. Alvarez, A. M. Ruiz, and J. E. Oviedo, «Optimal design of a diesel-PV-wind system with batteries and hydro pumped storage in a Colombian community », 6th International Conference on Renewable Energy Research and Applications (ICRERA), San Diego, pp. 234-239, 5-8 November 2017.

[15] I. Oukkacha, M. B. Camara, and B. Dakyo, “Energy Management in Electric Vehicle based on Frequency sharing approach, using Fuel cells, Lithium batteries and Supercapacitors”, 7th International Conference on Renewable Energy Research and Applications (ICRERA), Paris, pp. 986-992, 14-17 October 2018.

[16] B. K. Das and F. Zaman, “Performance analysis of a PV/Diesel hybrid system for a remote area in Bangladesh: Effects of dispatch strategies, batteries, and generator selection”, Energy, vol. 169, pp. 263-276, February 2019.

[17] V. Suresh, M. M., and R. Kiranmayi, “Modelling and optimization of an off-grid hybrid renewable energy system for electrification in a rural areas”, Energy Reports, vol. 6, pp. 594-604, November 2020.

[18] A. Kumar, Y. Deng, X. He, P. Kumar, and R. C. Bansal, “Energy management system controller for a rural microgrid”, The Journal of Engineering, vol. 2017, pp. 834-839, January 2017.

[19] M. Usman, A. M. Malik, A. Mahmood, A. Kousar, and K. Sabeel, “HOMER Analysis for Integrating Solar Energy in Off-Grid and On-Grid SCO Telecommunication Sites”, 1st Global Power, Energy and Communication Conference (GPECOM), Nevsehir, pp. 270-275, 12-15 June 2019.

[20] A. Aziz, M. Tajuddin, M. Adzman, M. Ramli, and S. Mekhilef, “Energy Management and Optimization of a PV/Diesel/Battery Hybrid Energy System Using a Combined Dispatch Strategy”, Sustainability, vol. 11, pp. 683-709, January 2019.

[21] C.-T. Tsai, T. M. Beza, E. M. Molla, and C.-C. Kuo, “Analysis and Sizing of Mini-Grid Hybrid Renewable Energy System for Islands”, IEEE Access, vol. 8, pp. 70013-70029, 25 March 2020.

[22] Y. Azoumah, D. Yamegueu, P. Ginies, Y. Coulibaly, and P. Girard, “Sustainable electricity generation for rural and peri-urban populations of sub-Saharan Africa: The “flexy-energy” concept”, Energy Policy, vol. 39, pp. 131-141, January 2011.

[23] D. Yamegueu, Y. Azoumah, X. Py, and N. Zongo, “Experimental study of electricity generation by Solar PV/diesel hybrid systems without battery storage for off-grid areas”, Renewable Energy, vol. 3, pp. 1780-1787, June 2011.

[24] D. Yamegueu, Y. Azoumah, and X. Py, “Experimental and economical study of sustainable electricity generation by solar PV/diesel hybrid systems without storage for off grid areas”, Energy and Sustainability 2011, Alicante, pp. 37-49, 11-16 April 2011.

[25] D. Tsuanyo, D. Aussel, Y. Azoumah, and P. Neveu, “Optimal Design of a PV/Diesel Hybrid System for Decentralized Areas through Economic Criteria”, International Journal of Computer, Electrical, Automation, Control and Information Engineering, vol. 9, pp. 486-491, 2015.

[26] D. Tsuanyo, Y. Azoumah, D. Aussel, and P. Neveu, “Modeling and optimization of batteryless hybrid PV (photovoltaic)/Diesel systems for off-grid applications”, Energy, vol. 86, pp. 152-163, June 2015.

[27] *S.* Ganesan, Ramesh V, and Umashankar S*,* “Hybrid Control of Microgrid with PV, Diesel Generator and BESS”, International Journal of Renewable Energy Research,vol. 7, pp. 1317-1323, Sepember 2017.

[28] E. Semshchikov, J. Hamilton, L. Wu, M. Negnevitsky, X. Wang, and S. Lyden, “Frequency control within high renewable penetration hybrid systems adopting low load diesel methodologies”, Energy Procedia, vol. 160, pp. 483-490, February 2019.

[29] J. Hamilton, M. Negnevitsky, X. Wang, and S. Lyden, “High penetration renewable generation within Australian isolated and remote power systems”, Energy, vol. 168, pp. 684-692, February 2019