Techno-economic study of a hybrid photovoltaic-diesel system for a remote area in southwest Algeria

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Article Info

Article history:

Received Mar 14, 2023
Revised Oct 29, 2023
Accepted Nov 7, 2023

Keywords:

Diesel generator
Emissions
HOMER
Power
PV systems
Solar energy

ABSTRACT

Exploiting natural sun and wind resources in remote and isolated areas is undoubtedly an excellent decision to generate electrical energy due to their availability and cleanliness. Various systems were used to generate this energy, such as photovoltaics (PV), wind turbine sand other energy systems. Moreover, for optimum energy use, some of these systems are combined either with each other or with other conventional systems, such as diesel generators with PV systems (i.e., hybrid systems). This work aims to present a technical-economic study of PV/diesel autonomous hybrid systems to supply electrical power for an isolated house located in a hot desert climate, Adrar. For optimizing the hybrid systems, hourly input data of solar radiation and load were used according to two configurations, where the annual load is 11.2 kWh/day. The findings showed that the diesel system had a high cost, with a cost for energy of \$0.407/kWh and a fuel price of \$0.140/l. Among the hybrid power systems but with significant pollution, the proposed hybrid system 2 kw photovoltaic and diesel generator with 2.3 kW has important economic feasibility, where the energy cost amounted to \$0.172/kWh. In addition, CO_2 emissions are reduced by approximately 5 tons every year compared to an independent diesel generator system.

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1. INTRODUCTION

Energy saving is an important challenge for any country to face the increase in consumption resulting from the realization of new residential buildings and the development of public infrastructure, and the recovery of the industrial sector [1]. Therefore, governments strive to make the most of all available energy sources, whether traditional (oil, natural gas) or renewable (wind, solar). In fact, the use of renewable energies (especially wind and solar energy) is the best option to overcome the problems of difficulty in delivering energy supplies to remote areas due to distance, rugged paths, or high cost.

The role of renewable energies is not only to provide energy power but also to serve as a factor for social and economic development. Where, a little energy can revive all the hopes of a village or community in terms of development and quality of life (providing potable water, studying, storing vaccines, and telecommunications) [2]. Due to fluctuating sunlight or low wind speed in a location, the best solution for power generation is using hybrid method. A hybrid method is a technical form that integrates at least two energy production systems. Various types of hybrid technique have been studied and analyzed in the literature.

An autonomous PV-wind-diesel hybrid station was dimensioned by estimating the available daily energy potential and the requested power [3]. In the previous research [4], the study focused on evaluating the configuration and functionality of autonomous PV-DG hybrid power systems. Sawle *et al*. [5] carefully discussed the configuration, design, and optimization of a photovoltaics (PV)/wind/battery/distributed generation (DG) hybrid method system installed in a far place of India. Ghussain and Taylan in [6] presented the optimum dimensions of PV/wind hybrid energy systems with three cases maximizing the renewable energy underestimating the cost of energy (COE) and using the maximum renewable energy with the COE less. A techno-economic optimization of different hybrid energy sources that are renewable installed on Deokjeokdo Island was analyzed [7].

A hybrid system's analysis is very complex and requires precision. Many software tools have been developed in the literature for sizing, design, analysis, optimization, and economic study of different hybrid systems. In general, the popular software programs are HOMER, Hybrid2, RETScreen, and TRNSYS. Sinha and Chandel [8] introduced 19 programs with their main features and current status. Where, different hybrid systems have been studied and reviewed in various locations worldwide using these software programs. The study presented the status of the programs by providing a basic insight for the researcher to identify and use the appropriate tools to develop hybrid systems [8]. Bernal-Agustín and Dufo-López [9] presented a simulation, optimization techniques, and software instruments to emulate and sizing independent hybrid systems for providing electricity. Furthermore, it reviewed 37 software tools used to analyze the various systems and know the necessary data to identify the necessary device. As well as to the amalgamation analysis of green energy into diverse power structures under various aims [9]. Connolly *et al.* [10] review different programs that can be employed for renewable energy integration analysis. To begin with, 68 software were taken into consideration, but 37 were contained at the end, analysis in cooperation with the tool creators. Sharma *et al.* [11] studied and analyzed five hybrid power system simulation software most used during the past ten years: HOMER, RETScreen, iHOGA, energy PRO, and TRNSYS. The study focused on comparing the effectiveness of software according to the environmental assessment.

HOMER is a simulation program for various energy systems, whether renewable (photovoltaic and wind) or other systems (generators and electrical grid). The US Department of Energy's National Renewable Energy Laboratory developed the HOMER program. The program is generally employed in assessments of viability and in optimizing and sizing energy powers. Where the user selects the location, loads, and database for the different elements; then, the software simulates all system elements. Ashok developed a hybrid system using different components to reach an ideal system of hybrid renewable energy system (HRES) components with useful optimization techniques [12]. Shaahid *et al.* [13] presented a PV/generator hybrid system and employed the flexibility of system battery storage. The behavior of a hybrid energy system that uses renewable resources to produce power was evaluated using a sizing program and displaying the operating mode and different structures of the system [14].

In the literature, the hybrid system's techno-economic analysis has been studied in several research papers to improve the capacity sizes of the different parts of the hybrid system and to find the ideal model in terms of total net present and cost COE [15]–[18]. To provide effective and sustainable solutions to preserve fossil energy resources and protect the environment, Algeria plans to launch an ambitious program to develop renewable energies [19]. Algeria contains a huge stock of solar energy due to its geographical location. Where, the average duration of sunshine exceeds 2,000 hours annually throughout the country [20]. This paper aims for a feasibility techno-economic and the payback period of using a hybrid photovoltaic/diesel generator system as a power source to generate power energy for a family residence in Adrar, Algeria. As well as checking the effectiveness of hybrid systems compared to diesel generators using HOMER software. The study can be expanded to homes with similar load demand in places with identical meteorological weather conditions.

The principal aim of this paper is to give an appropriate solution to the problem of electricity delivery to agricultural lands, which are far from the electrical network, where hundreds of farmers in the various settlements face great suffering due to the absence of electricity, in addition to the problem of agricultural tracts that is presented sharply in the various regions of the state. It should be noted that the state of Adrar has an area total farming exceeds 373550 hectares which only 34640 hectares are currently exploited. Therefore, we suggested studying a hybrid system to provide a house with electricity at a low cost to encourage farmers to settle and exploit the largest possible area of these lands.

2. METHODOLOGY

2.1. Site description

Adrar is one of the southwestern states of Algeria located approximately 1,200 km from the capital. The region has a latitude of 27.52 north and a longitude of 0.17. The region is characterized by important abilities of renewable energy due to its geographical location. Figure 1 represents location and map of the Adrar, Algeria.

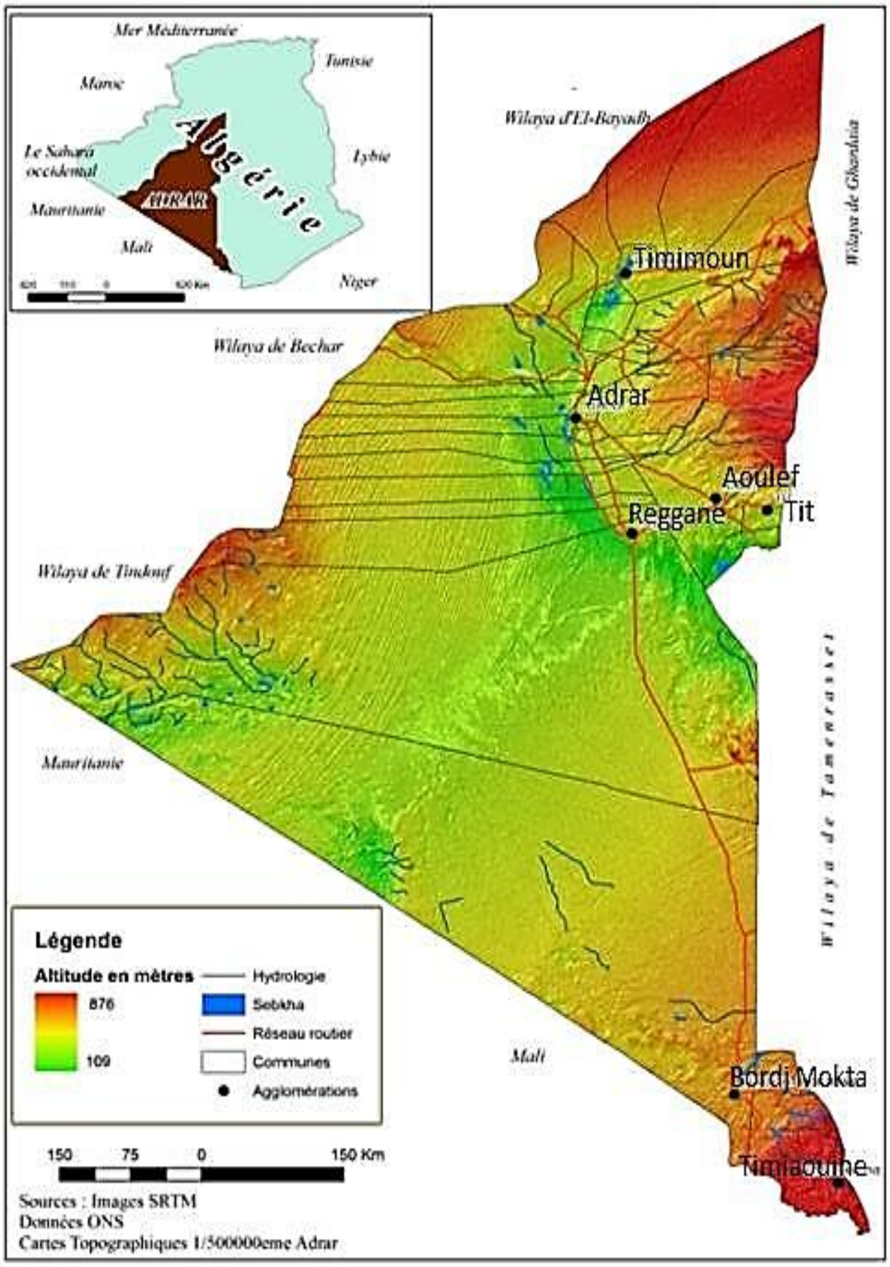


Figure 1. Location and map of the Adrar, Algeria [21]

2.2. Solar energy

We relied on the National Aeronautics and Space Administration web page to obtain Sunlight radiation globally data for the region. As shown in Figure 2, the irradiance of solar is relatively elevated in the summertime and low in the wintertime. The daily solar radiation index reaches its highest value in July, at 7.82 kWh/m^2/day, and in December, the lowest value was recorded, at 3.5 kWh/m^2/day. Solar radiation is available 12 hours a day [22], and it has been proven that solar energy potential in the area is substantial.

2.3. Electrical load consumption

After calculating the load, the average load of scaled annual is 11.26 kWh/day with a random change of 10% per day and an upper payload of 2.09 kW. Figure 3 shows the daily profile of electrical load for the study area. To take advantage of the available energy resources, two different types of energy were chosen to supply the electricity needs for the study area. The power models are the solar PV system and diesel generator. The higher energy consumption is between 17:00 h and 21:00 h, with a peak at 18:00 h, and the lower consumption of energy is between 00:00 h and 04:00 h in the morning hours.

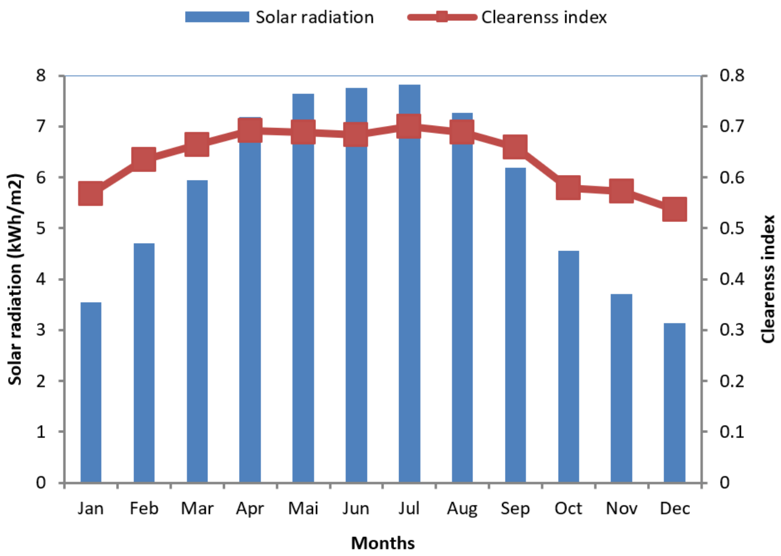


Figure 2. Profile average of monthly solar radiation and clearness index of Adrar

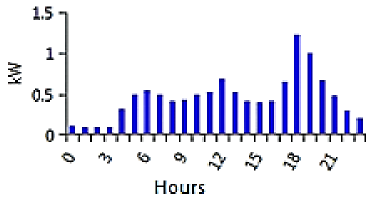


Figure 3. Daily electrical load profile

2.4. System configuration

Figure 4 shows the configuration of HOMER system. There are five main elements, diesel generator, solar panels, inverter, batteries, and load. The total load is 11.26 kWh/d.

2.4.1. PV model

A photovoltaic system uses photovoltaic panels consist of a collection of solar cells in series-parallel to provide DC electricity; the photovoltaic panel power output is presented by (1) [23].

$$P_{PVout} = P_{PVrated} * \left(G/G_{ref}\right) * \left[1 + K_T\left(T_c - T_{ref}\right)\right] \quad (1)$$

Where P_{pvout}: is the power output of the PV cell; $P_{pvrated}$: is the power rating of PVs under reference conditions; G: is radiation of sun (W/m2); G_{ref}: is sun radiation under normal temperature conditions (Gref = 1000 W/m2); T_{ref}: is reference parameters for cell temperature (Tref = 25°C); K_T: is the temperature coefficient of photovoltaic panels; Tc = Tamb + (0.0256 9 G), where Tc is temperature of cell and Tamb is surrounding temperature. The PV panel has capital and replacement cost of $700 and $0, respectively, with a lifespan of 25 yr

2.4.2. Inverter

The converter's choice depends on the PV Array's overall power [24]. In this design, we have an inverter with 2.30 kW. The inverter lifespan was assumed to be 10 yr, and the capital cost was $230/kW, while the replacement cost was $203/kW.

2.4.3. Battery

The battery is used to store electrical energy when needed. The storage element selection for the system is BAE SECURA SOLAR 12 V 1 PVS 70 with acapacity of 10 kWh, which has a cost of capital, is $780 and a cost of replacement is $760. The nominal capacity is 10.5 kWh.

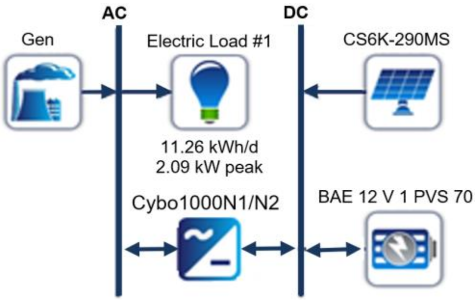


Figure 4. Hybrid PV-diesel system model in HOMER

2.4.4. Diesel generator

In this design, the diesel generator is very important as a fallback when the sun goes down and when the rain falls, so we chose the canon DG with a power of 2.3 kW, as the capital cost of the generator was $1,150/kW, the fuel use for diesel generators F_g(l/h) was represented by (2) [25].

$$F_g = A_G * P_{Gout} + B_G * P_{Grated} \tag{2}$$

Where P_{Grated}: the diesel generator nominal power; P_{Gout}: how much power is generated; A_G and B_G: represent the coefficients of the user-defined fuel consumption curve (l/kWh).

HOMER determines the cost of energy as the average price in kWh of electrical power generated by the system. To calculate the COE, divide the yearly cost of producing power by the overall output of electricity, according to (3) as researches [26]–[29].

$$COE = \frac{C_{at}}{E_{ser}} \tag{3}$$

Where C_{at}: overall system annualized cost ($/yr); E_{ser}: the overall output of electricity(kWh/yr).

The net present cost (NPC) is the main economic output of the company HOMER. The total amount of power produced, and every other financial result are computed to find the NPC. The NPC is computed using (4) [30], [31].

$$NPC = \frac{C_{at}}{CRF(i.Rp)} \tag{4}$$

Where capital recovery factor (CRF): factor of capital recuperation; i: rates of interest (%); Rp: lifetime of project (yr). The CRF is a result of the real interest rate for the year (i) and life time of the project. CRF is determined by (5) [32].

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

The real interest rate for the year is considered by (6) [16].

$$i = \frac{i_n - f}{1+f} \tag{6}$$

Where I_n: the rate of nominal interest (%); f: is the rate of inflation per year (%).

The payback period defines the expected period the project demands to regain its starting price. The initial cost of the project is recovered fast whenever the recovery period is short. The payback period (PBP) is considered by (7) [33].

$$PBP = \frac{I_0}{I_1} \tag{7}$$

Where I_0: starting price of a particular project; $I1$: the first-year cash flow. The system's costs include: i) capital cost; ii) replacement cost; and iii) maintenance (O&M) and operation cost [34].

The capital cost in this study installed for a 2.30 kW diesel generator will be approximately $1150, with an alternative replacement at $1571 and O&M costs at $0.164/hour. The cost of fuel in Algeria is approximately $0.2/liter. The PV panel's initial capital cost 2.02 kW is $700, cost of the replacement is $0, and the cost of operation/maintenance is $10/year. The lifetime of the photovoltaic panels is 25 years. For the inverter, a converter of 2.30 kW is used. The cost of capital is $230, the replacement price is $203, the cost of operation/maintenance is $5/year, and the efficiency is 96%. The battery capital cost is $780, cost of the replacement is $760, and the costs of O&M $65/year. For more details, see Table 1.

Table 1. Specific parameters of elements of the diesel/photovoltaic hybrid system

Description	Specification	Description	Specification
Panel model	CS6K-290MS	Battery model	SECURA SOLAR 12 V 1 PVS 70
Size	2.02 KWp	Nominal capacity	10.5 KWh
Capital cost	$700/kW	Capital cost	$780/kW
Cost of replacement	$0/kW	Replacement cost	$760/kW
Lifetime	25 yr	Nominal voltage	12 V
Inverter mode	CyboEnergy Off-Grid Twin-pack C1	Generator model	Autosize Genset
Rated power	2.30 KW	Rated power	2.3 KW
Capital cost	$230/kW	Capital cost	$1,150/kW
Cost of replacement	$203/kW	Replacement cost	$1,571/kW
Efficiency	96%	Lifetime	15.000 h
Lifetime	10 yr		

3. RESULTS AND DISCUSSION

In the simulation processes, HOMER calculates the price while determining the feasibility of the hybrid power system Throughout the year with a list of system configurations. Its capabilities are classified according to the least price of the equipment of NPC. After the simulation, different configurations were created, as shown in Figure 5. This study evaluates one scenario among several component energy systems to find the optimal configuration. It is discussed technically and economically.

The results of the simulation by HOMER for specific parameters are shown in Table 2. Over the course of the project, the total NPC for power supply is $9143.This system's inexpensive installation cost plays an essential part in the overall NPC. Additionally, this system has a COE of $0.172 $/kWh, the operating cost is $486.02, and the payback period is about 1.58 years.

The hybrid system's economics presentation is predicated on presenting the total costs associated with the system in an individual manner for each participating element. The costs associated with the mixed system are presented in each component of system and cost type. The cash flow summary of the various elements in the hybrid system, such as the Diesel generator, PV modules, batteries, and power converters, shows that the total NPC is the highest for the Diesel generator and the lowest for the inverter. The capital price, cost of replacement, and operating price of the presented hybrid system are about $2.860, $2.730, and $2.779, respectively, noting that the salvage cost is $236.02 as seen in Figure 6.

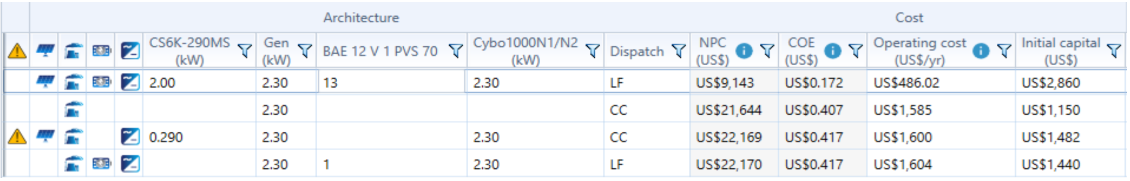
Figure 7 shows the amount of power generated each month during the year of the suggested renewable energy hybrid system. The annual energy generated from diesel generators was 1261 kWh/year (25.56%), while for the photovoltaic system, it reached 3672 kWh/year (74.43%). Table 3 demonstrates the PV operation results when the total electrical production output is 3672 kWh/year and 4380 hrs/year. The PV is 2.02 kw when solar insolation completely available and 0 kw when the panel is not getting enough solar energy.

Table 2. The system's installation and operating costs

System	Cost system
Initial capital	2860 $
Operating cost	486.02 $
Cost of energy	0.172 $
Total NPC	9143$

Table 3. PV system operation results

PV system	Quantity
Hour of operation	4382 hrs/year
Electrical production	3672 kWh/year
Min electrical output	0
Max electrical output	2.02 kW



Architecture									Cost			
					CS6K-290MS (kW)	Gen (kW)	BAE 12 V 1 PVS 70	Cybo1000N1/N2 (kW)	Dispatch	NPC (US$)	COE (US$)	Operating cost (US$/yr)	Initial capital (US$)
					2.00	2.30	13	2.30	LF	US$9,143	US$0.172	US$486.02	US$2,860
						2.30			CC	US$21,644	US$0.407	US$1,585	US$1,150
					0.290	2.30		2.30	CC	US$22,169	US$0.417	US$1,600	US$1,482
						2.30	1	2.30	LF	US$22,170	US$0.417	US$1,604	US$1,440

Figure 5. PV-diesel system configuration

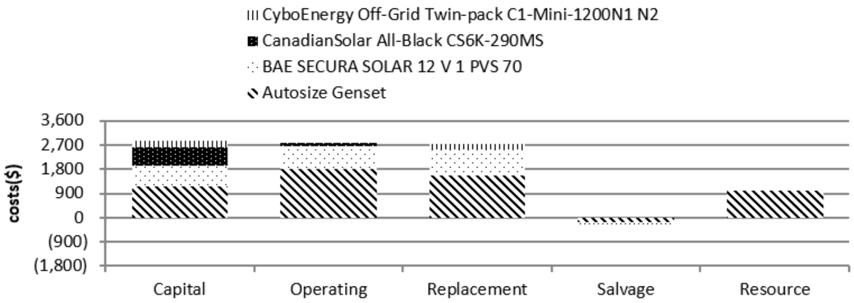


Figure 6. The PV/DG hybrid system cash flow summary

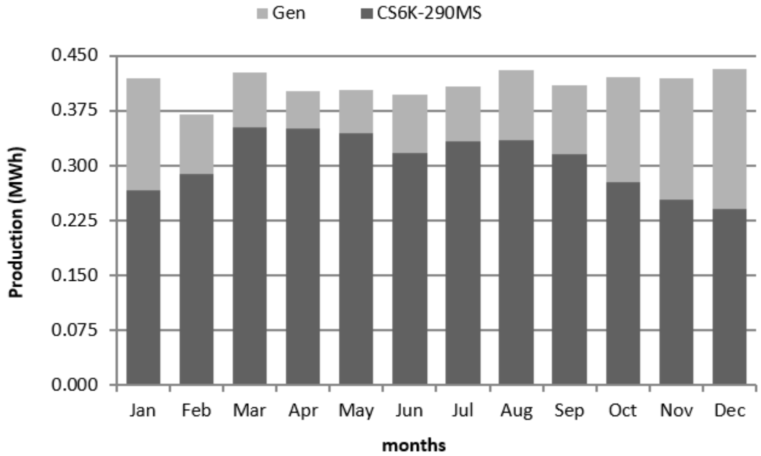


Figure 7. Average electricity output of the PV/diesel hybrid system per month

As shown in Figure 8, at 07:00 and 19:00 am there is no production of electricity, and there is considerable power generation during the daytime. The power comes close to the nominal power of the module, reaching a value of 2 kW at 12 pm, in certain periods in year. In the winter months, this power decrease, due to the lower level of insolation. To meet the electricity demand in this system, diesel generators must operate 2028 hours/year. As indicated by Table 4, a DG uses 558 liters of fuel to generate 1261 kWh/yr.

Renewable energies are considered one of the world's most sustainable, effective clean, and performance. Table 5 shows the number of pollutant emissions of carbon monoxide, dioxide of carbon, nitrogen oxides, unburned hydrocarbons, and sulfur dioxide, where we note the proportion of carbon dioxide in the case of the diesel generator is 6432 kg/year. This percentage is high for the photovoltaic/diesel hybrid system, which is approximately 1462 kg/year, meaning that the hybrid system reduces carbon dioxide emissions by 77.26% less, and is the best choice.

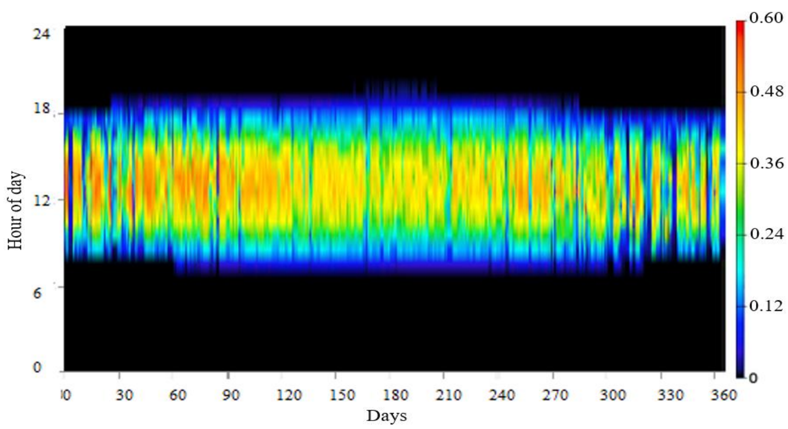


Figure 8. The PV power output during the days

Table 4. Results of DG operation

Diesel generator	Quantity
Operation hours	2028hrs/yr
Fuel consumption	558 L
Electricity generation	1261 kWh/yr
Minimum power production	0.575 kW
Maximum power generation	1.96 kW
Mean electrical output	0.622 kW
Mean electrical efficiency	23%

Table 5. The diesel generator's polluting emissions

Pollutant hybrid	Quantity	
	PV/Diesel	Only diesel
Carbon dioxide	1462 kg/yr	6432 kg/yr
Sulfur dioxide	3.58 kg/yr	15.7 kg/yr
Nitrogen oxides	8.66 kg/yr	38.1 kg/yr
Monoxide of carbon	9.21 kg/yr	40.5 kg/yr
Unburned hydrocarbons	0.402 kg/yr	1.770 kg/yr
Particulate matter	0.0558 kg/yr	0.246 kg/yr

The hourly distribution of the average energy generation by the DG for the years' months is shown in Figure 9. As can be observed, for months with higher average of PV panels, the generator is almost not used since PV panels is capable of meeting demand. For the rest of the year, this component only works for specific periods of the day, to support the PV system. The pollutant emission quantities for the PV/DG system and diesel are displayed in Table 5.

Figures 10-12 presented the effect of photovoltaic penetration on carbon emissions, usage of diesel fuel, net present cost, excess energy generation, and cost of energy. The line diagram of Figure 10 indicates the impact of photovoltaic penetration on net present cost and cost of energy, Where the COE and NPC increase when the value of PV penetration increases. It also illustrates that for a $0.085 increase in COE, there is a nearly $8456 increase in NPC.

Figure 11 shows that diesel fuel consumption and carbon emission decrease when the value of PV penetration increases, as an increase of 1% in PV penetration results in a decrease of 7% (150 liters/year) and 18% (1011 tons/year) of diesel fuel consumption and carbon emission, respectively. Increases in diesel prices have led to an increase in energy cost and, on the contrary, a decrease in renewable energy fraction (REF). Figure 12 present effect of photovoltaic penetration on excess energy and the COE. An increase of $0.01/liter diesel price increases COE by almost $0.011/kWh. For more explicit, Figure 13 shows the detail.

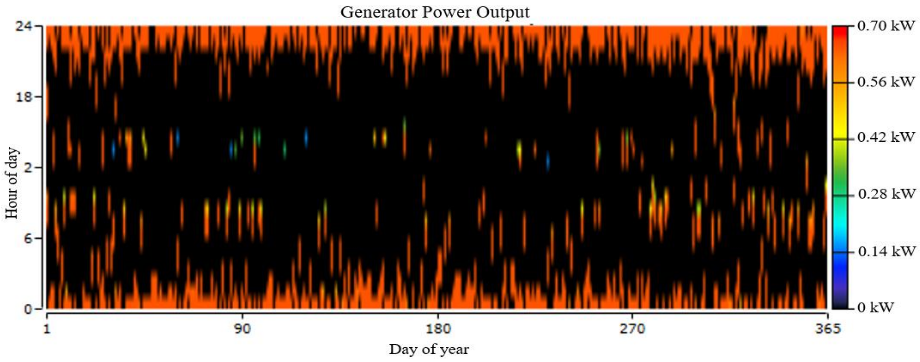


Figure 9. Generator power output during the days

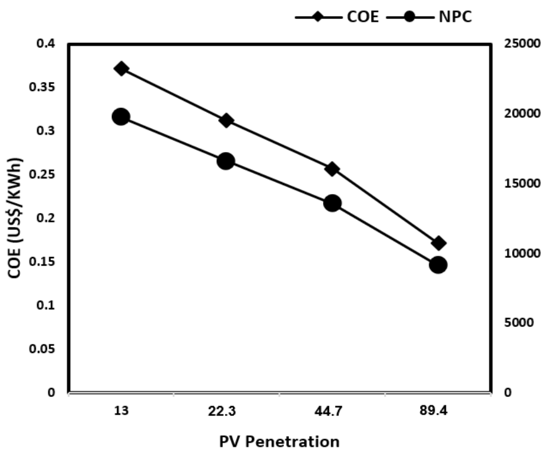


Figure 10. Impact of PV penetration on the COE and NPC

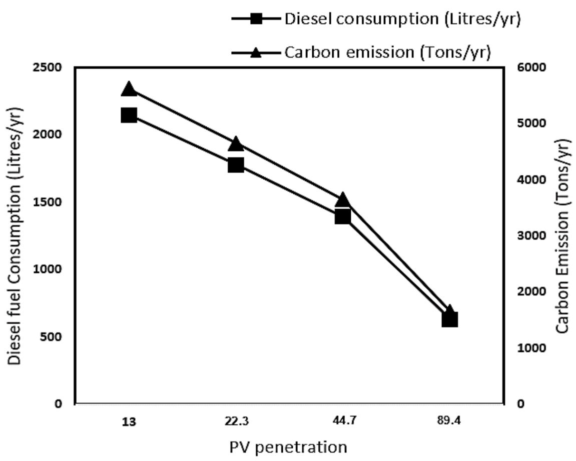


Figure 11. Effect of photovoltaic penetration on carbon emission and usage of diesel fuel

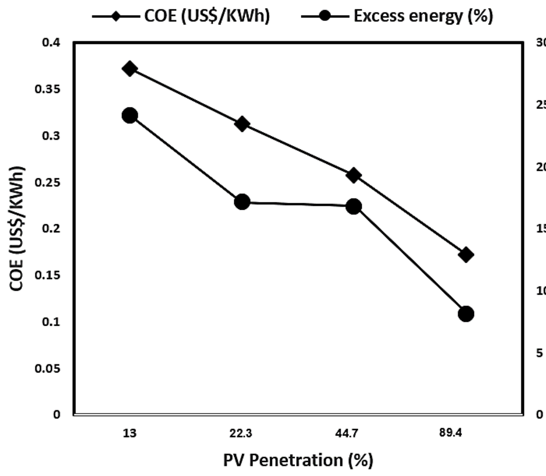


Figure 12. Effect of photovoltaic penetration on excess energy and the COE

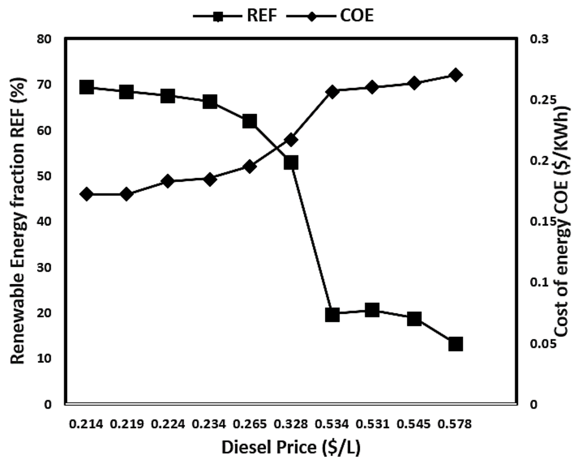


Figure 13. Impact of diesel fuel cost on renewable energy fraction and cost of energy

4. CONCLUSION

This paper presents an investigation into a hybrid system for renewable energy in a rural area isolated from the electrical network in Adrar, Algeria. The different energies involved in the operation of this hybrid system depend more on the photovoltaic modules' surface area than on the batteries' storage capacity. This study shows that it is not desirable to configure the system with a storage capacity greater than three days of battery life because when this value is exceeded, the impact of an increase in capacity becomes negligible. The economic study of the cost of producing an electric kWh has shown that it varies and that the best system is the one that provides one kWh at lowest cost. The PV/DG hybrid system for producing electrical energy is based on knowledge of the site's energy potential and after evaluating the daily need of isolated residences. The result showed that PV/DG hybrid system is an excellent solution. The initial capital and NPC are $2762 and $9458.20, respectively. The system energy cost is $0.420/kWh, while the payback period of the cost investment for the hybrid PV/DG system is 1.58 years, with the renewed fracture is 13%. It also found that the PV/DG hybrid system has lower CO2 emissions throughout operation of the DG. The results are hoped to assist decision makers in the country in the region's future energy planning and provide a different approach to the country in energizing isolated places. because of the big development of the electricity domain in Algeria on the one hand the ability to produce and the dissemination of the grid, the economic and technical analysis is required to support the country's future endeavors. The durability and lifetime of the system's performance depend on the short payback period. This is reflected in improving the country's economy by efficiently providing electricity.

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