Planning Optimization of a Standalone Photovoltaic/Diesel/Battery Energy System for a Gold Mining Location in Mauritania

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ABSTRACT

The greenhouse gas emissions resulting from the excessive use of Diesel Generators (DGs) in mining locations pose a threat to the environment and the macroeconomic sustainability of this industry. This paper aims to decrease or eliminate the use of DG units in gold mining areas to increase access to more clean Renewable Energy Sources (RESs) such as Photovoltaic (PV) systems. In order to evaluate PV potential at small-scale gold mining sites in Mauritania, ArcGIS software is utilized to analyze Chagatt gold mining location as a case study. The techno-economic viability of a PV/DG/battery Hybrid Energy System (HES) was examined and discussed. For yearly modeling, the PVsyst and HOMER Pro were employed to assess the performance of the ideal size of HES in terms of installation and energy costs. The findings indicate that Mauritania's gold mining locations are most suitable for PV energy harvesting. As a result, this industry may rely on clean PV energy.

Keywords-rural energy systems; gold mining; PV/diesel/battery system; autonomous generation

I. INTRODUCTION

The majority of rural and remote communities are located in distant or isolated areas where it is expensive to transmit energy using conventional power systems, causing a lack of electricity accessibility [1]. Over 562 million people without access to electricity reside in sub-Saharan Africa [2], due to present economic and technical obstacles to extend the grid [3]. In Mauritania, many rural areas suffer from inadequate electricity coverage [4]. Furthermore, the rising of artisanal and small-scale gold mining operations since 2016 has made the situation worse. These mining locations are typically outside of the grid coverage and are powered by small Diesel Generators (DGs), as evidenced in Figure 1, which are not adaptable to the changing demand of the mining equipment and not environment friendly [5]. DG units have a high cost of fuel and delivery to remote locations [6]. Also, these generators pose threats to the environment and human health [7], so it is important to reduce their usage. Renewable Energy Systems (RESs) are becoming a major unit as they constitute autonomous energy systems capable of electrifying rural communities. The installation, operation, and maintenance costs of RESs, regarding the off-grid electricity demand is a tempting factor. However, these RESs, and especially PV and wind power cannot cover the demand for a 24-hour load due to their intermittent nature. Thus, it is necessary to install HESs that combine batteries and DG units. The effectiveness of PV/ DG /battery HES for electric energy production in rural areas has been assessed by many research papers [8-14]. HESs are proved to be an economical and ideal option for sustainable energy. Compared to a PV/battery system, HES requires 70% less batteries and guarantees consistent energy supply. Also, HES saves CO_2 emissions by up to 97% when compared to the traditional DG units. Authors in [15, 16] conducted a techno-economic analysis on HES for isolated Indian islands. Their proposed system uses four Battery Energy Storage (BES) technologies. Many control schemes have been proposed for higher fuel savings and minimizing the daily running time of DG units. Authors in [17] introduced a scheme that enhances the rural load profile, resulting in cost effective energy production.

Fig. 1. Environmental damage of small out of service DGs

Authors in [18-20] demonstrated the feasibility of decreasing the use of DG in favor of PV systems, which leads to significant savings over a project's life, based on actual data from Lagos, Nigeria. This economical method lowers the dangers connected with DG while facilitating the switch to a greener RES [21]. The electrification of remote mining activities, which are typically located outside of the grid coverage need a seasonal behavioral modeling. Authors in [22] showed that a combination of a heavy fuel oil power plant with a PV system to power mining activities allows for lower fuel consumption [23]. The evaluation of cost minimization is assessed thanks to many simulations which have provided energy analysts and designers with more knowledge. For instance, the Canadian gold mining corporation Kinross has disclosed its intention to invest 55 million USD to construct a PV energy plant in Tasiast mine in Mauritania with the PV potential ranging from 1,900 to 2,200 kW h/m^2/year [24].

Mauritania has abundant RESs, especially in the PV sector. In order to strengthen their economy, the Mauritanian government is seeking to increase the electricity it supplies and to promote investment in RESs [25]. The application, load demand, meteorological data, and geographic location of this study set it apart from related studies. The goal of this paper is to persuade Mauritanian gold miners to switch to RESs integrated with a DG serving as a backup source [26]. Using the ArcGIS software, the methodology followed assesses the solar radiation in the Maaden corridors area, which contains most of the gold mining locations [27]. The location distribution of all small-scale gold mining pathways in Mauritania is necessary for the method to map the solar radiation and hence for PV system planning. Maaden database is the data source of the northernmost point at the border between Mauritania and Algeria, in Chagatt [28]. Thus, the energy needs of gold miners are calculated. Climate data employed in this study are derived from Metronom, which is a comprehensive database of meteorological information that is utilized in energy planning simulations [29]. Additionally, many algorithms are applied to calibrate meteorological data and modify a wide range of meteorological characteristics to compute values on an hourly and per-minute basis [30]. Also, PVsyst software was deployed to simulate the complete PV system based on the required input data. It provides data on predicted potential solar radiation, energy production, and installation expenses for standalone, grid-connected, and PV pumping systems. Two designs have been compared for economic viability using a life-cycle cost analysis. Finally, Homer Pro optimization software wasw employed to carry out economic analysis, and so create the best optimized configuration.

II. RELATED WORKS

Efficient small scale energy systems can reduce dependency on mainland power and lower energy costs. Current technological research favors RESs for power generation in self contained power networks and ignores alternate demand management strategies [31]. Authors in [32] proposed an intelligent system to solve intermittent energy source demand-supply difficulties. Operational efficiency and component size reduction could minimize system costs.

Authors in [33] examined freestanding solar load amplitude shifting. They observed that power generation load profile change boosts performance. In [34], the modeling analysis conducted found the lowest levelized energy cost for the load profile closest to the PV generating profile [35]. Authors in [36] modeled a solo solar-wind-fuel cell energy system to evaluate its efficiency. Authors in [37] sized stand-alone hybrid solar-wind systems using turbine height, PV tilt angle, and PV, wind turbine, and battery module quantities. Lost Power Supply Probability (LPSP) affected the model's fitness variable levelized electricity cost. Efficiency decreased with maximal LPSP. High LPSP severely impacts operations and services with tight low tolerances. Increased LPSP from 1% to 2% lowered PV module and wind turbine power generation, cutting system cost to 8.5%, displaying how LPSP parameters affect system output. Authors in [38] developed an off-grid hybrid system that generates AC electricity from PV, wind, and diesel power. Authors in [39] combined three battery technologies to construct an efficient battery power bank with different cell types to optimize benefits and minimize drawbacks. The paper emphasized system accessibility and reliability, since independent DGs prevented power shortages. Collaboration on system-wide battery technologies is another priority. Authors in [40] carefully studied lead-acid, lithium-ion, and vanadium redox-flow batteries and analyzed the cycle efficiency, age, and condition for each battery type. Authors in [41] implemented a novel amenity metric to evaluate power supply. They related end-use demand to comfort indicators like air quality, carbon dioxide, interior temperature, and illumination instead of LPSP. The method followed in [42] employs a mathematical model to determine occupant discomfort from unmet end-use expectations instead of setting a maximum LPSP. This technique has two advantages over the model's LPSP: First, it used data points on all-time series during modeling. LPSP may prioritize resource optimization over power outage. In contrast, in [43], the comfort level method simulated effects better over unmet time. The pain technique gives each time series point distinct discomfort. The model could be improved to represent occupant comfort with higher pain levels. The Boolean variable LPSP could be applied to each time-series point to indicate that electrical loss limited its versatility. Calculating comfort variables and restrictions complicates optimization. In the current study realistic weighting variables were needed because comfort preferences differ.

III. MATERIALS AND METHODS

A. Site Description

An isolated area, the Chegatt corridor, in Tiris-Zemour state (latitude: 25.37 N, longitude: -5.79 W, altitude: 380 m), at the northernmost point of the border between Mauritania and Algeria, was used to evaluate the PV/ DG /battery HES proposed for gold mining. The miners claim that Chegatt, which has developed into a sizable gold mining zone, is exceptionally rich in gold. There are strong signs that gold has been mined in this region historically, such as in Chami and Gleib Ndour, and 650 soldiers are already stationed there to provide security. December 15, 2020, was the planned opening date for gold miners in Chegatt, which is an 104,000 km^2 approved area. Since there are no official statistics, it is unknown how many gold miners are in this area. Gold miners purchase fuel from stations in Zewrat town and utilize DG to supply their electricity demands.

B. Climatic Conditions

The climate data utilized in this investigation were sourced from Meteonorm, which is used to assess the meteorological parameters for the case study location. Figure 2 portrays the monthly precipitation levels and the frequency of rainy days.

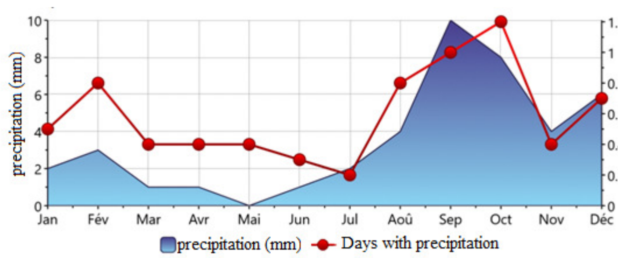


Fig. 2. The actual rain (mm) vs. days with precipitation

Figure 3 depicts the monthly global irradiance on horizontal and angled surfaces at an optimal angle of tilt of 30°.The monthly irradiance varies between 3.25 and 7.59 kWh/m^2/d. Figure 4 displays the estimated annual average temperature of 37°C and the mean daily irradiance of 5.63 kWh/m^2/d. Between January and June, irradiance levels on both horizontal and angled surfaces exhibited a rising pattern [44], reaching their highest point in June and July and then begining to decrease. The highest amounts of irradiation on sloped surfaces were noticed between August and December, as well as from January to April.

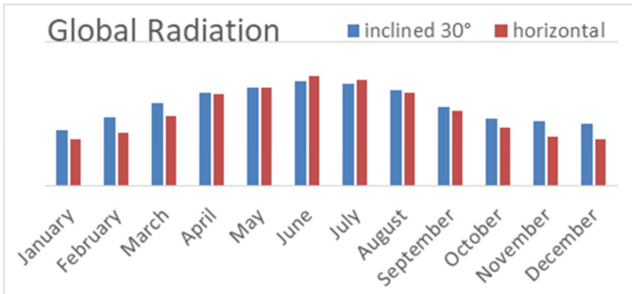


Fig. 3. Average monthly radiation for a given area

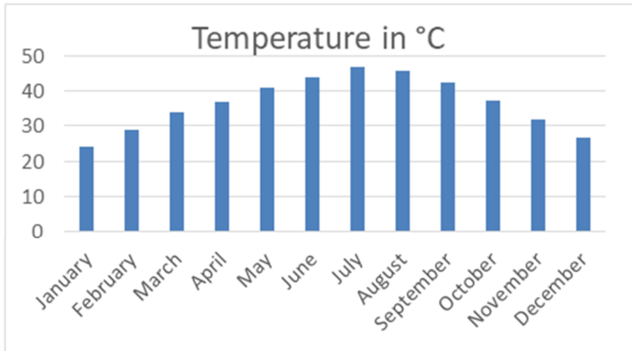


Fig. 4. Monthly temperature in °C.

C. Load Assessment

The load profile assessment is crucial because a wrong load profile can result in under- or over-sizing, which can have detrimental effects on the system. Some of the power tools utilized in this study include a fan for ventilation in shafts, a hammer for digging, lamps for nighttime lighting, and outlets for charging phones and laptops. Based on Table I, the daily energy requirement is 19.824 kWh. The power tools have been provided by a 3.5 KVA generator that uses 5 lt of fuel on a daily basis. Every day, the employees are in the office from 8:00 to 12:00 and from 15:00 to 18:00.

TABLE I. DAILY ELECTRIC ENERGY CONSUMPTION FOR A GOLD MINING LOCATION

Device	Number	Power (W)	Operating time (h/day)	Energy (Wh/day)
Jackhammer machine	1	1700	11	18700
Fan	1	50	8	400
Lamps	2	50	5	500
Phone / PC	2	50	2	200
Standby	1	1	24	24
Total daily energy			19,824 kWh/day	

D. Sizing Procedure

As observed in Figure 5, the parts of the suggested PV system are a PV array, inverter, charge controller, a battery, and a backup DG. A description of these elements follows.

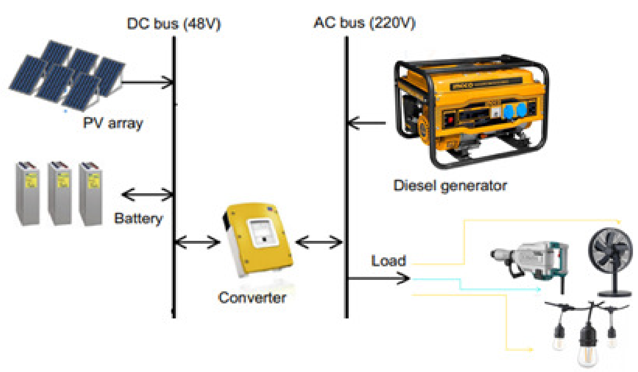


Fig. 5. The proposedHERS diagram

PV panel sizing: The solar radiation absorbed depends on the load demand, the estimated surface PV area to be installed, and the selection of additional equipment (inverters, controllers, etc.) which can be used to design a PV system. PV panel sizing for the former to be connected in series is determined via the following formula:

$$N_{pv-serial} = \frac{D_{energy}}{E_{worst} \times \eta_{batt} \times \eta_{reg} \times \eta_{lines}} \quad (1)$$

where η_{batt} is the battery efficiency , η_{reg} is the electrical efficiency of the entire system, η_{Lines} is the lines' efficiency, and E_{worst} is the worst solar radiation

The maximum voltage of the PV panels is estimated by:

$$V_{pv-max} = 1.15 \times N_{pv-serial} \times U_{oc} \quad (2)$$

where U_{oc} is the open circuit voltage.

The modules of each parallel chain can be calculated as:

$$N_{pv-parallel} = \frac{U_{pv-max}}{V_{DC-bus}} \quad (3)$$

where U_{pv-max} is the operation maximum voltage and V_{DC-bus} is the DC bus actual voltage.

Next, the total number of panels is deducted:

$$N_{pv} = N_{pv-para}.N_{pv-serial} \quad (4)$$

The total PV energy to be installed will be:

$$P_{pv-total} = N_{pv}.P_p \quad (5)$$

where P_p is the operation power of the panel.

Battery sizing: BES capacity can be found using the following formula:

$$C_{batt}\,(A.\hbar) = \frac{D_{energy} \times N_{aut}}{V_{batt} \times DOD \times \eta_{batt}} \quad (6)$$

where V_{batt} is the BES voltage, DOD is the BES depth of discharge, η_{batt} is the BES efficiency, N_{aut} is the number of days of autonomy, and D_{energy} is the total energy required per day.

The number of batteries used is given by:

$$N_{batt} = \left[\frac{C_{batt}}{C_{batt,u}}\right] \quad (7)$$

where $C_{batt,u}$ is the BES unit capacity and C_{batt} is total BES capacity

Inverter sizing: It is based on AC loads and PV energy. Inverter power must be at least equal to (90-95%) of PV energy.

E. Economic Analysis

The life cycle cost (C_{LC}) analysis is deployed to assess the feasibility of the proposed HES by considering the initial investment cost (C_i), the operation and maintenance cost (C_{OM}), and the battery replacement cost (C_{BR}). It can be described by:

$$C_{LC} = C_i + C_{BR} + C_{OM} \quad (8)$$

The other costs of HES parts have been determined depending on the Mauritanian market situation (see Table II). The overall cost can be determined based on the equations below, where S is the size:

$$C_{batt} = S_{batt} \times C_{batt} \quad (9)$$

$$C_{pv} = N_{pv} \times C_{PV} \quad (10)$$

$$C_{inv} = S_{inv} \times C_{inv} \quad (11)$$

$$C_{chareger} = S_{charger} \times C_{charger} \quad (12)$$

TABLE II. THE COSTS OF EQUIPMENT USED IN THE PROPOSED HES

	PV	Charge controller	Battery	Inverter	DG
Cost	1.03 USD/Wp	5.43 USD/Amp	2.12 USD/Ah	0.77 USD/W	0.3 USD/W

The total initial investment cost C_i is expressed as:

$$C_i = C_{PV} + C_{inv} + C_{batt} + C_{cc} + C_{in} + C_{acc} + C_{DG} \quad (13)$$

where C_{PV} is the cost of PV modules, C_{inv} is the cost of the inverter, C_{batt} is the cost of the batteries, C_{cc} is the cost of the charge controller, C_{in} is the installation cost (estimated at 10% of the overall PV system's cost), C_{acc} is the cost of the accessories (estimated at 5% of the overall PV system's cost), and C_{DG} is the cost of the DG.

The PV system has a 20-year lifespan, therefore over the project's duration, the batteries—which have a 5-year lifespan need to be changed three times. The battery replacement cost is represented by (14), where *r* represents the number of replacements:

$$C_{BR} = C_{batt} \times \sum_{j=1}^{r} \left(\frac{1+i}{1+d}\right)^{Nj/(1+r)} \quad (14)$$

The operating and maintenance costs can be found by:

$$C_{OM} = [C_i + CFC] \times \left(\frac{1+i}{d-i}\right) \times \left[1 - \left(\frac{1+i}{1+d}\right)^N\right] \quad (15)$$

where i is the inflation rate (2.5%), d is the discount rate (5%), and CFC is the cost of fuel consumption.

Equation (16) yields the power cost unit. Moreover, (17) yields the PV system's life cycle cost:

$$COE = \frac{AL_{cc}}{365 \times D_{ele} \times S_f} \quad (16)$$

$$AL_{cc} = L_{cc} \times \left(\frac{1-\left(\frac{1+i}{1+d}\right)}{1-\left(\frac{1+i}{1+d}\right)^N}\right) \quad (17)$$

where AL_{CC} is the PV system's annual life cycle, L_{CC} is the life-cycle cost, D_{ele} is the daily electric demand, COE is the cost of energy, and S_f is the PV fraction of supply.

IV. RESULTS AND DISCUSSION

Mapping the areas where gold mining occurs (mineral corridors) and the areas where sunlight occurs over these areas, it can be observed that among the Sahelian-Saharan nations, Mauritania is the one that has acknowledged gold mining the most. Since the country's gold-mining corridors are spread throughout remote areas without access to electricity, gold-panners rely on DGs. The total yearly radiation, on the other hand, ranges from 1908 to 2280 kWh/m^2, with the northern region, which is home to the majority of the gold-mining corridors, having the greatest levels, as indicated by the red and yellow zones in Figure 6. Stakeholders can identify locations that are suitable for PV power generation with the aid of estimates of solar radiation. Furthermore, the amount of sunshine that is available to a stand-alone PV system relies on the latter when it is situated on a site.

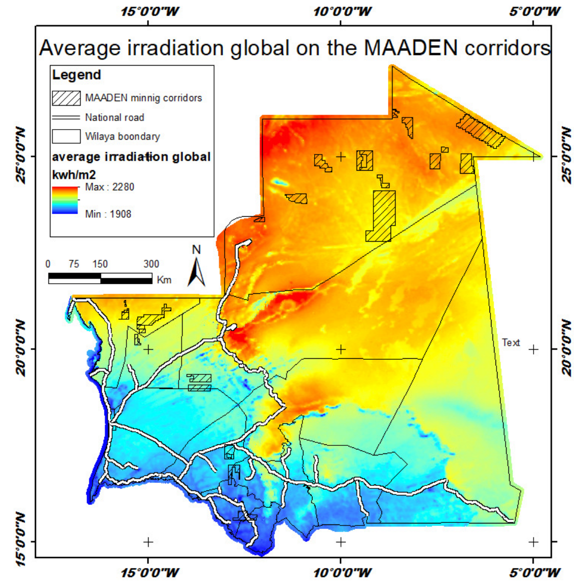


Fig. 6. Solar radiation distribution on the gold-mining corridors in Mauritania.

A. *Preliminary Sizing Results*

The above given equations were used considering the following assumptions: Charge controller, battery and power line efficiencies were assumed to be 86%, 85% and 75%, respectively. The number of days with constant cloud cover is two. The maximum depth of discharge that is allowed for batteries is 70%. The inflation rate is 1.5%. Finally, the discount rate is 2%. Gold mining needs a peak PV output of 7590 Wp, which can be produced by 33 PV panels connected in series and parallel, per (1), (3), (4), and (5). Equation (6) indicates that the BES's overall capacity is 800 Ah. The maximum battery current, or 3×8 = 24 A, has been selected to be handled by a charge controller (30A/48V). Furthermore, an inverter with a power of 6000 W and the technical specifications shown in Table III has been selected for this investigation. The DelSolar D6P230A3E PV module, whose maximum power is 230 Wc, has been chosen. Table III lists all its parameters. Since the chosen battery has a capacity of 100 Ah and a voltage of 12 V, there will be 8 batteries in total, as stated by (7). Four of these batteries need to be connected in parallel and two of them in series.

TABLE III. PV PARAMETERS OF DELSOLAR D6P230A3E MODULE

Characteristics	Value
Maximum panel power (*Pmax*)	230 W
Maximum panel operating voltage	29.49 V
Maximum panel operating current	7.80 A
Module efficiency	13 %
Short circuit current	8.39 A
Open circuit voltage	37.20 V
Power tolerance	+ 3%
Maximum system voltage	600 V
Fuse rating	15 V

B. Annual Simulation of The Dimensioned System

The PVsyst application was used to run the annual simulation that predicted the anticipated PV system's performance. When executing the simulation, the following variables were considered: Module tilt angle =30° (optimum tilt angle of project site). The PV modules face south (azimuth = 0). Meteorological data were monitored by Meteonorm. Table IV displays the PV portion, the energy produced by the backup generator, and the PV energy delivered to the user. With an average PV portion of 96%, it is evident that the intended system has the capacity to meet electricity demand for the majority of the year. The backup generator will cover the anticipated remaining energy use.

TABLE IV. ELECTRIC GENERATION BY PV SYSTEM

Month	Energy produced by PV (KWh)	Energy produced by the DG (KWh)	Total load (KWh)	PV fraction (%)
January	588.2	26.3	614.5	0.957
February	541.1	14	555.1	0.975
March	614.5	0	614.5	1.000
April	589.9	4.8	594.7	0.992
May	607.4	7.1	614.5	0.988
June	594.7	0	594.7	1.000
July	614.5	0	614.5	1.000
August	598.0	16.5	614.5	0.973
September	552.6	42.1	594.7	0.929
October	558.1	56.4	614.5	0.908
November	558.9	35.8	594.7	0.940
December	530.1	84.4	614.5	0.863
Yearly	6948.1	287.7	7235.8	0.960

C. Results of the Economic Analysis

Equation (13) determines the initial installation cost, C_i, which is 22733.87 USD. On the other hand, (14) and (15) calculate the battery replacement cost, CNR, which is 6191.64 USD, and the Operation and Maintenance Costs, COM, as 207.34 USD. Consequently, the life cycle cost of the proposed hybrid system was determined to be 0.67 USD/kWh, and the cost of energy produced was found to be 2913.85 USD. According to today's market standards, this cost is relatively high, so an optimization process was needed to improve the design and move it to the direction of a configuration that would be more profitable.

D. Homer Pro Optimization Results

Figure 7 illustrates the architecture selected for the proposed HES, which was optimized using Homer Pro software. Two buses make up this architecture: a DC bus that is connected to the PV panels and batteries, and an AC bus that is related to the DG and the load. A bidirectional inverter connects these two buses to one another. This gold panner's daily electricity consumption was 19,824 kWh/day, and the previously stated economic factors were applied.

Figure 8 depicts the ideal PV system layout. There are 6.52 kWp PV models, 4.6 kW arrays, 12 × 167 Ah batteries, and 3.65 kW inverter capacities among them. It is evident that the investment cost, which is now 18487 USD, has declined in line with the PV capacity's decrease from the original design. With this optimized arrangement, the energy unit cost has been significantly decreased and is calculated at 0.302 USD/kWh. Figure 9 displays the optimal configuration's average monthly power production. It is noticed that the improved layout has a lower PV percentage (93.7% vs. 96%) than the original design. Because of the subsidies offered by the government to make up for the use of conventional fuels, using DG to meet a portion of the energy demand is therefore a financially feasible solution in the current situation of the market.

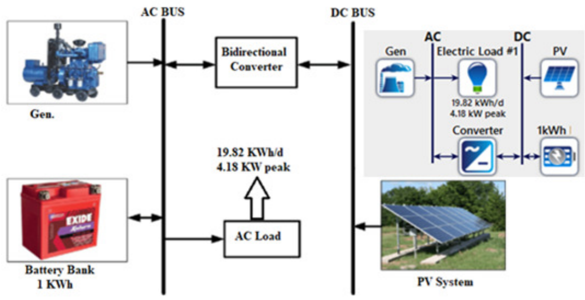
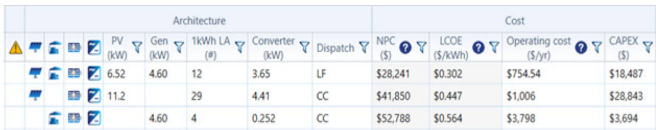


Fig. 7. Homer's simulatorHERS architecture.



	Architecture					Cost			
	PV (kW)	Gen (kW)	1kWh LA (#)	Converter (kW)	Dispatch	NPC ($)	LCOE ($/kWh)	Operating cost ($/yr)	CAPEX ($)
	6.52	4.60	12	3.65	LF	$28,241	$0.302	$754.54	$18,487
	11.2		29	4.41	CC	$41,850	$0.447	$1,006	$28,843
		4.60	4	0.252	CC	$52,788	$0.564	$3,798	$3,694

Fig. 8. Optimum system results

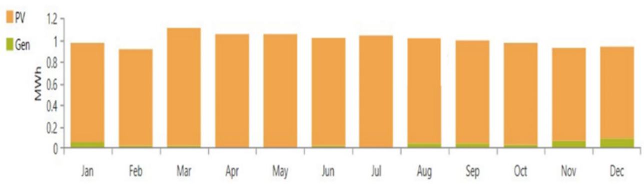


Fig. 9. Average monthly electricity production for the optimized configuration.

V. CONCLUSION

Adopting Renewable Energy Sources (RESs) is a viable solution to provide distant rural areas, such as gold mining locations, which are situated in rural areas, away from the grid, with energy. Small Diesel Generators (DGs) are utilized by gold miners to power their equipment but they are expensive and have negative environmental impacts. Therefore, more RESs are required for this purpose. This study aims to evaluate the PV/diesel/battery HRES to operate gold mining in Chagatt. The proposed autonomous Hybrid Energy System (HES) (PV/ DG/battery) has been analyzed and fully dimensioned in the second phase to meet the demand of a gold-panner (19,824 KWh/day). The annual evaluation has been implemented utilizing the PVsyst program to forecast the Photovoltaic (PV) system performance. Finally, an ideal design based on Homer Pro software has been proposed. With a daily energy usage of 19. 824 kWh, a gold panner needs 400 Ah of battery storage and 6886 Wp of PV energy, with an average PV percentage of almost 96%. By decreasing the PV energy share to 6.52 KW and increasing the DG energy share, the unit cost of energy can be lowered from 0.65 USD/kWh to 0.302 USD/kWh.

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