JJEE
Volume 7, Number 2, June 2021
Pages 84-95
Jordan Journal of Electrical Engineering
ISSN (Print): 2409-9600, ISSN (Online): 2409-9619

Sizing and Analysis of a DC Stand-Alone Photovoltaic-Battery System for a House in Libya

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Received: February 10, 2021 *Revised: March 19, 2021* *Accepted: March 24, 2021*

***Abstract*—** This paper presents an isolated Photovoltaic (PV)-battery system for fulfilling the load of a typical house located in Benghazi, Libya. 48 V DC is considered as the bus voltage. The proposed system has been sized using HOMER Pro software and found to consist of 28 PV panels, 330 watts each, and 32 lead-acid battery banks of 12 V, 219 Ah. The dynamic model of the system is implemented in MATLAB/Simulink software. The results show that the proposed system can provide a stable 48 V DC for the intended load. It can also be used to meet the electricity needs of houses with low loads or rural communities with basic electricity needs. The performed economic analysis reveals that the proposed system - with a net present cost of $42,892 - can generate electricity at a cost of $0.365/kWh, indicating that such a system will make economic sense in remote off-grid areas.

***Keywords*—** Stand-alone PV-battery system; DC distribution system; Techno-economic analysis; HOMER Pro.

1. INTRODUCTION

For several years, Libya has relied heavily on oil and natural gas to produce electric power. However, population growth and economic activities caused a significant increase in the electrical energy demand that estimates between 6% to 8% per year [1, 2]. Recent fluctuations in oil prices lead to pressure on the financial resources of the state. Also, environmental impacts from using conventional energy sources are a paramount concern these days. Libya should seriously consider alternative solutions to face these challenges. Renewable energy (RE) sources are a promising solution to contribute to minimizing these impacts. Even though Libya is rich in RE sources, it has not utilized them on a large scale [3].

Libya is the second-largest country in North Africa, with about 1,750,000 Km^2 and 6.93 million population. The most population is concentrated in the northern part of the country and only 10 % live in the southern region [4]. Successive governments have focused on the people's spatial development - by investing in electric power - to prevent them from moving from the south and rural areas to the north. The investment in transmission lines, substations, and generation stations caused high costs to the state treasury. The civil war in Libya caused severe damage to the electrical grid, which led to a severe deficit of electrical power, forcing the control center's engineers to implement load shedding to keep the grid from breakdown. Power load shedding hours in Tripoli reached about 16 hours in summer 2019 [5]. According to the 2018 multi-sector needs assessment (MSNA), residents of the southwest regions faced frequent power cuts for 6 to 11 hours per day [6]. As a result of this dilemma, several citizens have resorted to diesel generators. However, The growth in diesel fuel demand has led to an increase in its price, making this solution unattainable by many people.

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Article's DOI: 10.5455/jjee.204-1612977821

Libya is located between latitudes 20° N and 32° N and between 10° E and 25° E longitudes. This prime location contains a large resource of solar energy. The average daily direct radiation in the northern and southern parts of the country is 8.1 kWh/m^2/day and 7.1 kWh/m^2/day, respectively while the sunshine hours are over 3500 per year [7]. Some details are shown in Fig. 1 [8]. It indicates a high potential for solar energy in this region, which can be utilized as alternative source to cover electricity needs. Two standard techniques are used to benefit from solar energy: i) converting direct solar energy into electricity, which is known as photovoltaic (PV) technology and ii) converting natural sunlight energy into thermal energy identified as solar energy concentration technologies [9].

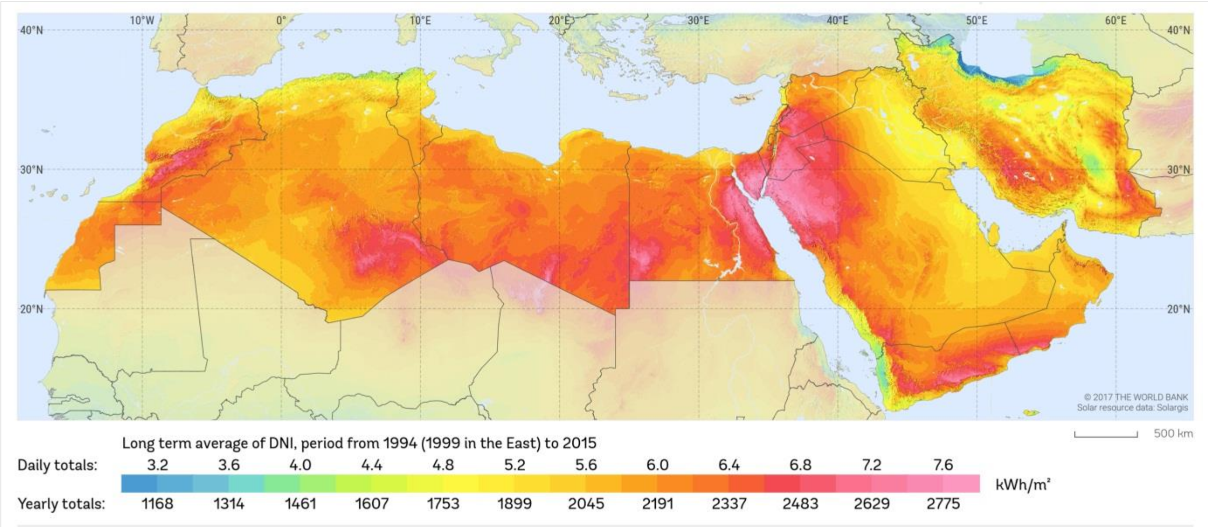


Fig. 1. Direct average irradiation in the Middle East and North Africa.

In the late 1880s and early 1890s, there was a competition between AC and DC to transmit electrical energy, known as the war or the battle of currents. At the end, AC was adopted to carry power over long distances due to the possibility of using high voltages, which means less current and, consequently, fewer losses in the transmission lines [10]. As a result of the extensive development in the semiconductor industry, various household gadgets these days run internally on DC power, where the AC power from the electrical grid is converted to DC power by internal transformers or a converter.

PV systems are considered one of the clean energy sources that produce DC power directly. The conversion losses from AC to DC can reach 30%. Moreover, the lack of need for an inverter reduces the capital cost [10]. In [11], a logarithm was proposed to determine the most efficient design of a solar energy system, including the option of an AC or DC supply system. The results show economic efficiency in the solar PV system for residential loads with many DC load ratios. The distribution systems for AC and DC power in a residential environment of an average family were compared using a developed mathematical structure, taking into account the determinants affecting the performance, such as house architecture and the load distribution. The analysis is done by the electrical transient analyzer program (ETAP). After the comparisons were made on the nominal AC voltage of 220 V with various DC voltages for typical wire (size 4 American wire gauge), the results showed that 48 V DC is 4% and about 9% more efficient than 380 V DC and AC 220 V, respectively [12]. Therefore, for isolated houses, 48 V DC is the best solution. It is safe and capable of running most of the house load. DC appliances are commonly available in the market these days.

This paper aims to present a suitable stand-alone PV-battery system for remote houses to meet the challenges resulting from damage to the network due to violent events in Libya. A 48 V DC is used instead of 220 V AC to supply the house and to increase efficiency of the independent system. The case study of this search is a typical house in Benghazi, Libya. Sizing and design of this system is the objective of this research. This paper is divided as follows: section 2 illustrates the structure of the design and sizing. Sections 3 provides detailed economic analysis. Section 4 demonstrates the dynamic modeling, simulation, and the results. Finally, the conclusions are presented in section 5.

2. SYSTEM SIZING AND STRUCTURE

2.1. Site Selection and Electrical Loads

As a case study, a typical house located in Benghazi, Libya, has been considered. Determining the household's energy demand is essential to design the proposed PV-battery system. For this purpose, electricity bills were obtained from the General Electricity Company of Libya (GECOL). They include the energy consumption of the house (see Table 1).

Table 1. The monthly energy consumption for a house in Benghazi, Libya.

Period of reading		Numbers of days	Consumption [kWh]
From	To		
08/12/2016	15/03/2017	97	2962
15/03/2017	05/06/2017	82	1456
05/06/2017	28/09/2017	115	3394
28/09/2017	18/12/2017	81	1545
Total		375	9,357

Based on the energy consumption for 375 days which equals 9,357 kWh, the daily energy consumption is calculated and found to be 24.9 kWh/day. As shown in Fig. 2, the peak load occurs between 17:00 and 21:00, which is expected for the residential load as most household activities happen in the evening.

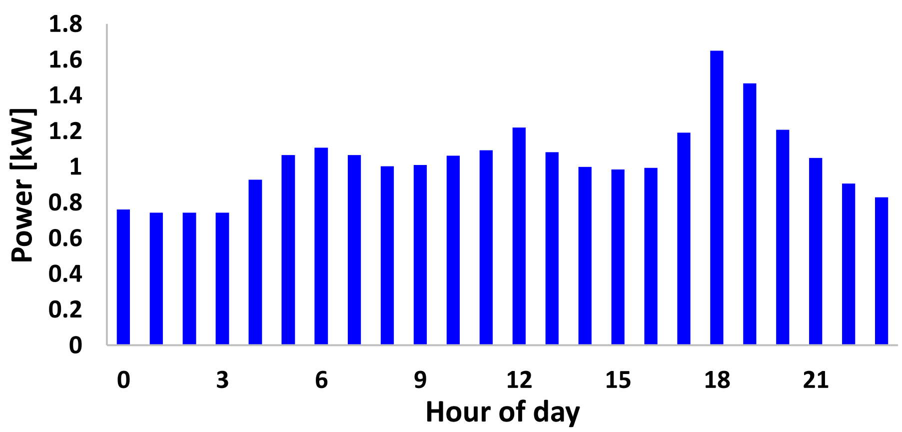


Fig. 2. Daily profile of the residential load.

2.2. Solar Irradiation Resources

Libya is among the countries that have an excellent potential for solar energy. The proposed PV-battery system will be utilized to serve the demand load of a house in Benghazi, Libya which is located at a location of 32°5.5'N latitude and 20°7' E longitude. The Hybrid Optimization of Multiple Energy Resources (HOMER) Pro software of the National Renewable Energy Laboratory (NREL)/ USA involves a database with solar resources worldwide from NASA's data [13]. As shown in Fig. 3, the solar resource has been generated by selecting the proposed system's location. The scaled annual average solar irradiation is 5.44 kWh/m^2/d.

Fig. 3. The monthly average solar radiation at the selected location.

2.3. Components of the Proposed PV-Battery System

To study the effectiveness of utilizing PV systems in supplying direct DC loads, HOMER Pro software was utilized, and provided with the proposed system's load, which was assumed to be converted to DC. A 48 V DC bus was chosen due to the high efficiency among other DC voltage for residential loads. A PV panel (CANADIAN SOLAR MAXPOWER2 CS6U-330P 330W POLYOLAR PANEL) consisting of 72 Cells, and lead-acid trojan battery (SSIG 12205) were selected [12]. Simulation is done in HOMER Pro software to obtain the optimal size of the PV-battery system's components. The diagram of the proposed PV-battery system is shown in Fig. 4.

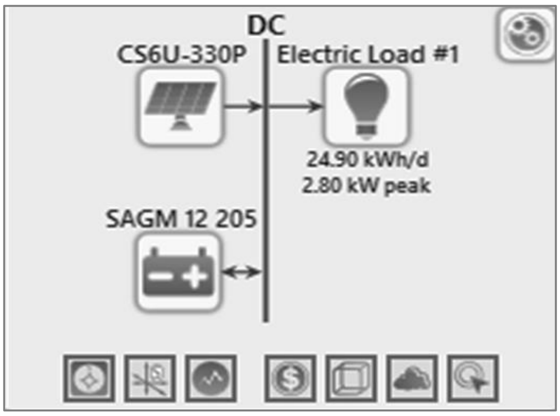


Fig. 4. Schematic diagram of the proposed PV-battery system

During the simulation process, HOMER Pro software considers different numbers of solar panels and batteries to reach the most cost-effective system that entirely fulfills the load demand. Based on HOMER Pro optimization results, the desired system consists of 28 PV panels. Each of these panels produces 330 W, and it is composed of 72 poly-crystalline cells. The system also includes 32 lead-acid battery banks producing 12 V, 219 Ah to store excess generated electricity and to feed the load at night and in the bad weather. Simulation results are shown in Figs. 5 and 6.

Fig. 5. Monthly energy production of the proposed PV-battery system.

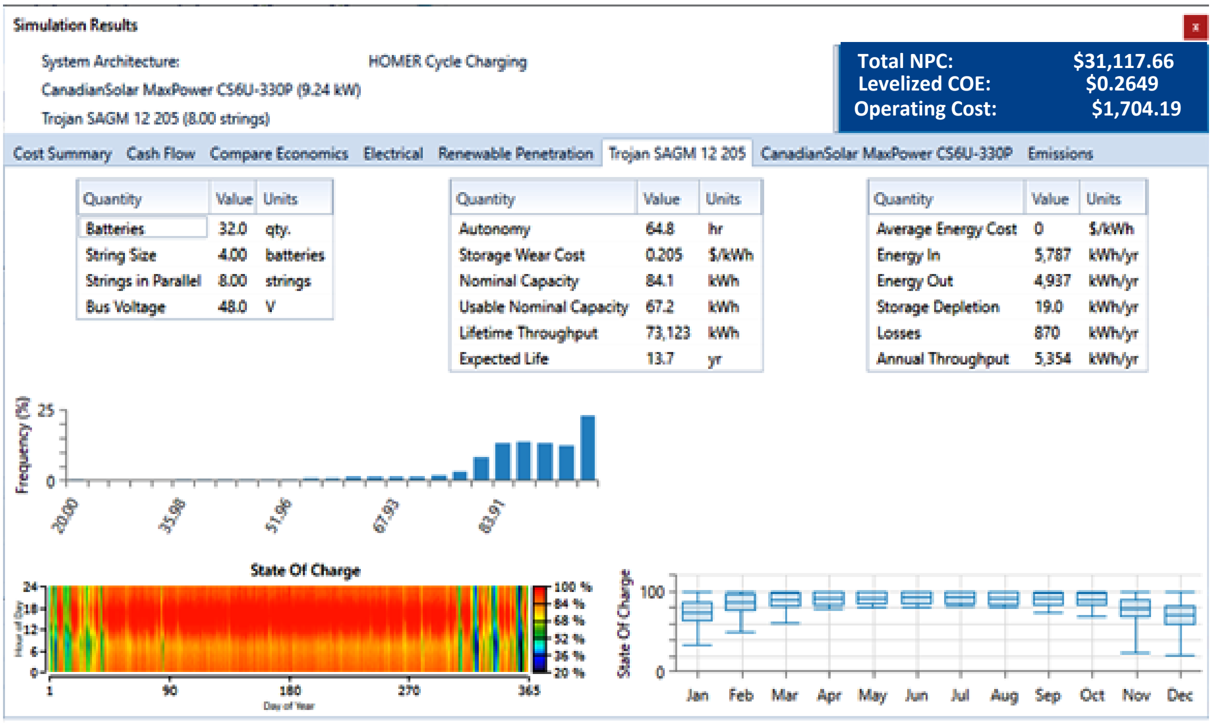


Fig. 6. Results for the utilized battery bank of the proposed PV-battery system.

Fig. 7 exhibits the proposed electrical wiring diagram of the proposed PV-battery system. House appliances such as refrigerator, freezer, water pump, water heating, and small AC are coupled directly to 48 V DC. A buck converter steps a voltage down to 12 V DC to supply light bulbs and small electronic loads such as TV, computers, etc.

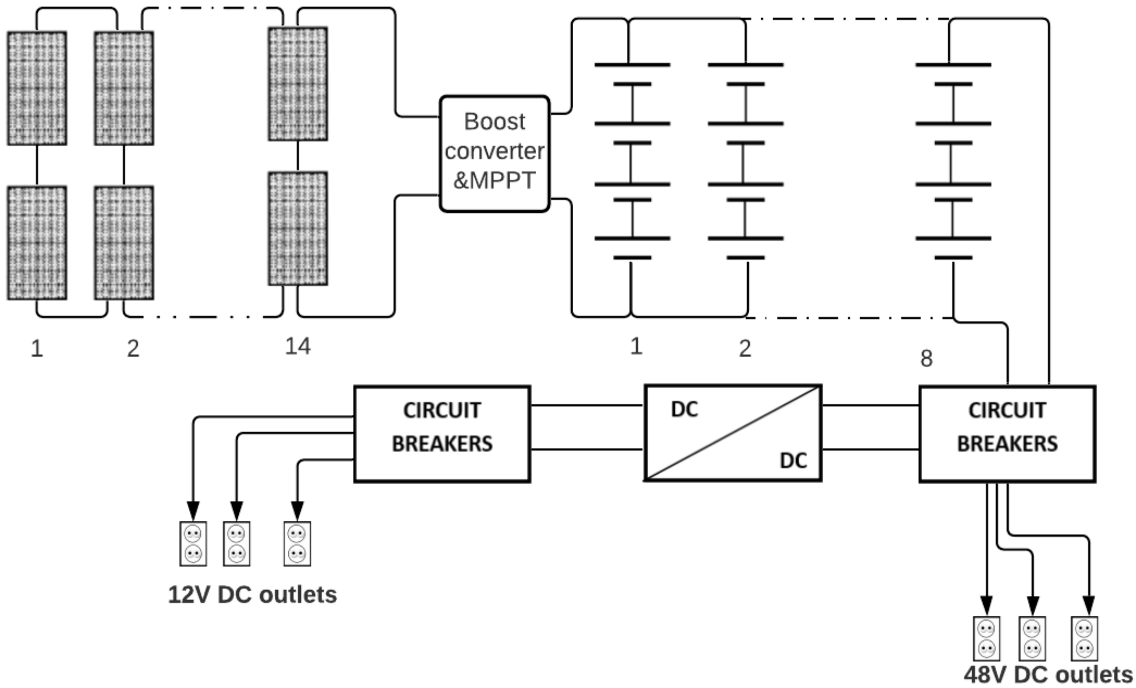


Fig. 7. Layout of the proposed PV-battery system and the DC distribution in the house.

The clothes are dried outside in the open air. Propane is used for cooking and occasionally for heating for space waiting if needed in the winter. Therefore, such loads are not included in the system design.

3. ECONOMIC ANALYSIS OF THE STAND-ALONE PV-BATTERY SYSTEM

Since the system proposed in this study is an isolated one, it was compared to: i) the mostly used independent power source in Libya, namely the diesel generator and ii) a hybrid system comprised of PV panel, diesel generator and a battery (PV-Gen-Batt), the schematic diagram of which is exhibited on Fig.8. Technical specifications and cost data for each of the individual components of the aforesaid systems are listed in Table 2.

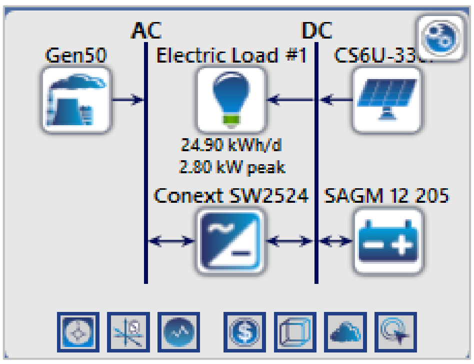
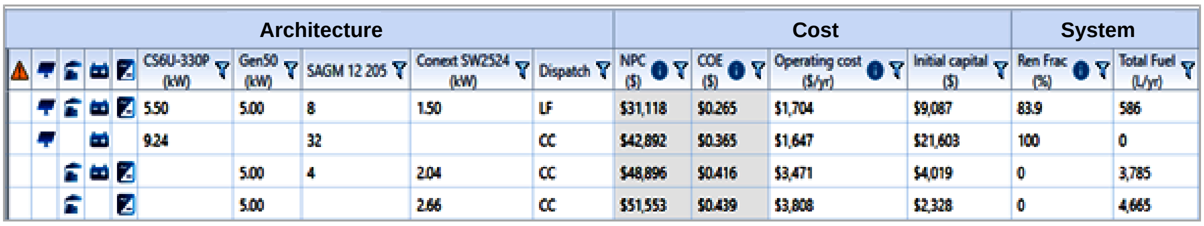


Fig. 8. Schematic diagram of the hybrid PV-Gen-Batt system.

Table 2. Technical specifications and cost data of the investigated systems' individual components.

Component	Rating	Numbers of components	Cost /unit [$]	Total cost [$]
PV panel	330 W	28	200	5,600
Battery	12V, 219 Ah	32	500	16,000
Converter	3 kW	1	1500	1500
Diesel generator	5 kW	1	1000	1000

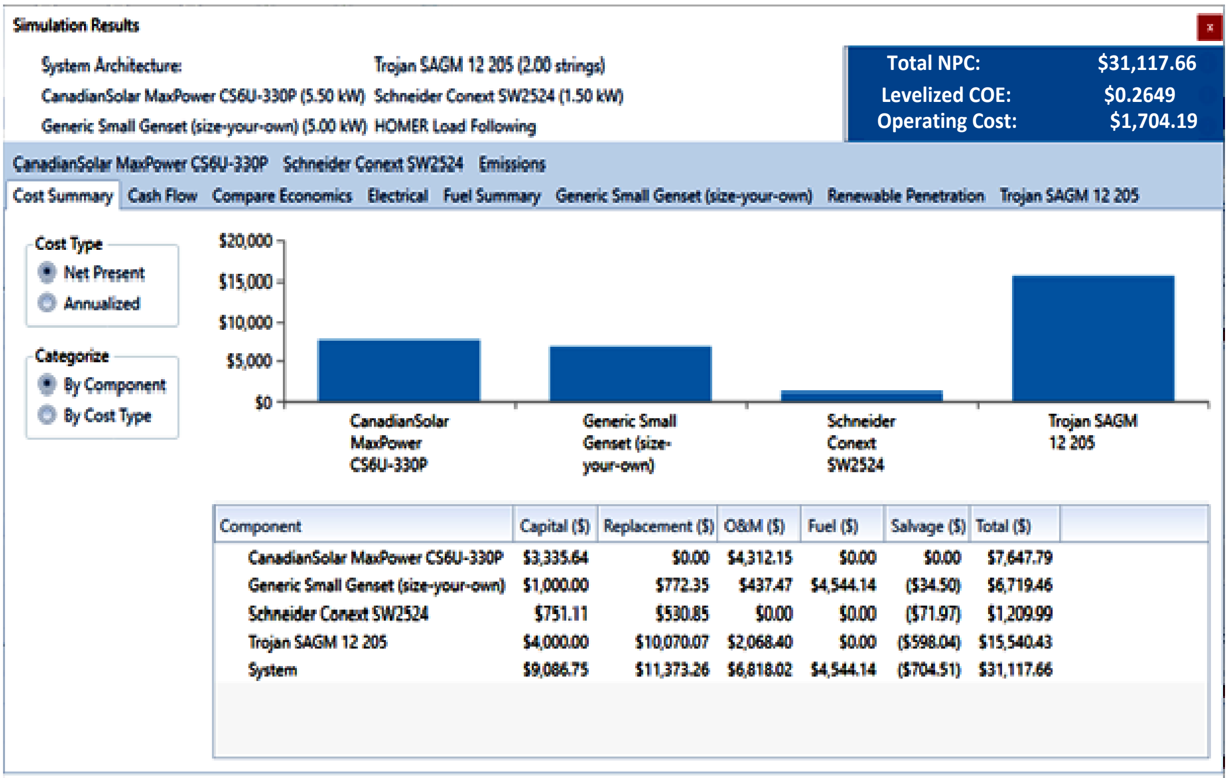
Fig. 9 shows the HOMER Pro optimization results for the considered systems. It lists the most optimal systems based on the net present cost (NPC) and cost of electricity (COE).



Architecture					Cost				System	
CS6U-330P (kW)	Gen50 (kW)	SAGM 12 205	Conext SW2524 (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)
5.50	5.00	8	1.50	LF	$31,118	$0.265	$1,704	$9,087	83.9	586
9.24		32		CC	$42,892	$0.365	$1,647	$21,603	100	0
	5.00	4	2.04	CC	$48,896	$0.416	$3,471	$4,019	0	3,785
	5.00		2.66	CC	$51,553	$0.439	$3,808	$2,328	0	4,665

Fig. 9. Optimization results for the investigated systems.

The results reveal that the hybrid PV-Gen-Batt offers the least NPC and COE with $31,118 and 0.265 $/kWh, respectively. Cost summary of this hybrid system is summarized in Fig. 10.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
CanadianSolar MaxPower CS6U-330P	$3,335.64	$0.00	$4,312.15	$0.00	$0.00	$7,647.79
Generic Small Genset (size-your-own)	$1,000.00	$772.35	$437.47	$4,544.14	($34.50)	$6,719.46
Schneider Conext SW2524	$751.11	$530.85	$0.00	$0.00	($71.97)	$1,209.99
Trojan SAGM 12 205	$4,000.00	$10,070.07	$2,068.40	$0.00	($598.04)	$15,540.43
System	$9,086.75	$11,373.26	$6,818.02	$4,544.14	($704.51)	$31,117.66

Fig. 10. Cost summary of hybrid PV-Gen-Batt system's components.

As shown in Fig. 9, the PV-battery system comes in the second place among the optimal systems with a COE of 0.365 $/kWh. Although 87% of annual electricity produced in the hybrid PV-Gen-Batt system is by PV panels, as shown in Fig. 11, it was selected as an optimal option instead of the isolated PV-battery system. This is due to the fact that the NPC and, consequently, the COE of the PV-battery system is affected primarily by cost of batteries representing about 70% of the total system's cost, as shown in Fig. 12.

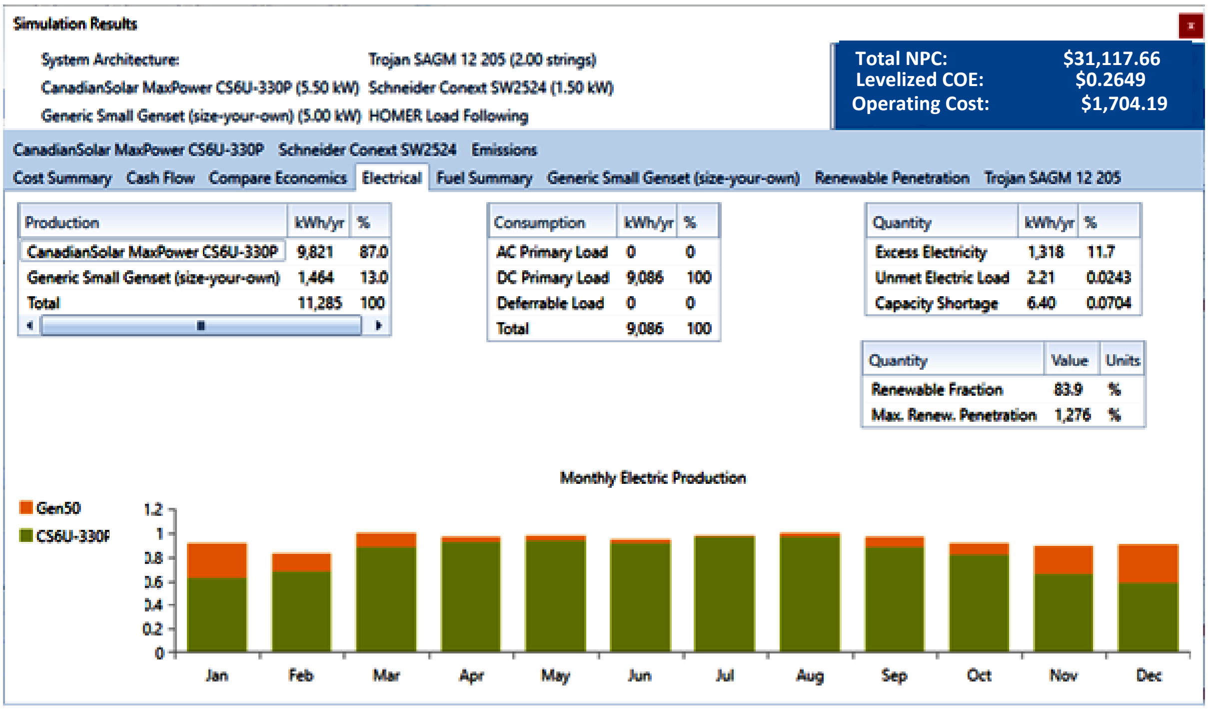


Fig. 11. Electrical simulation results for the hybrid PV-Gen-Batt system.

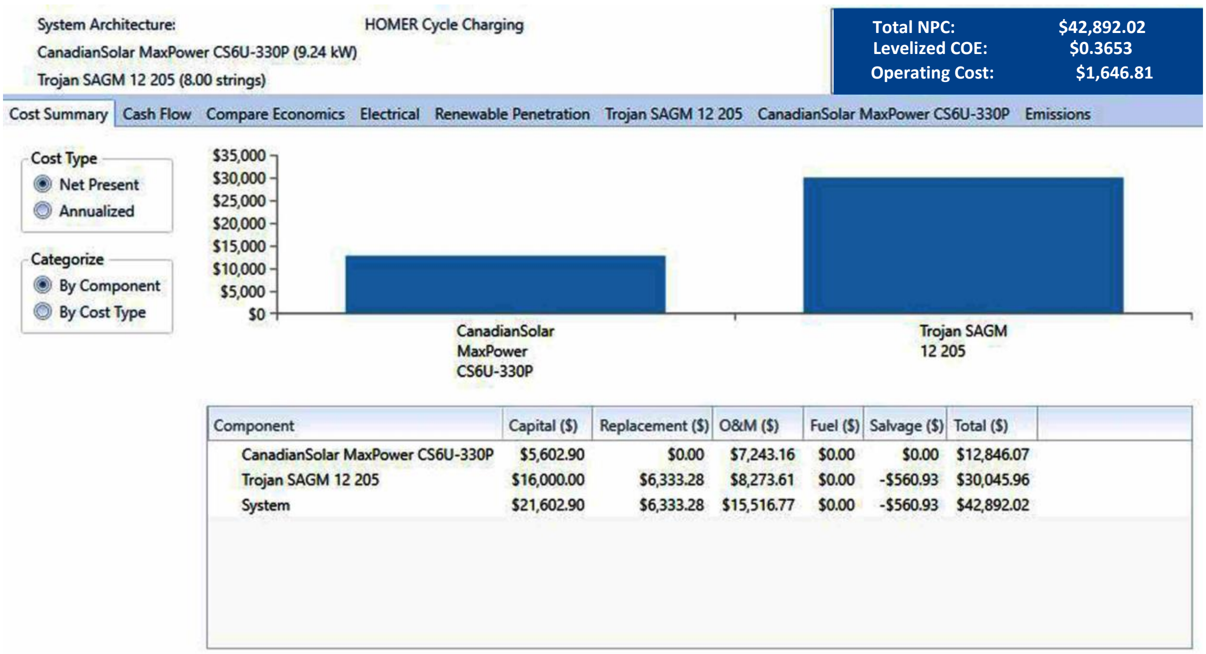


Fig. 12. Summary of the PV-battery system cost results.

Despite the cheap diesel price in Libya (0.11 $/L), the diesel generator only system is considered a poor economic and a more expensive option compared to the rest of the investigated systems. It has - as summarized in Fig. 13 - NPC and COE of $51,553 and 0.439 $/kWh, respectively.

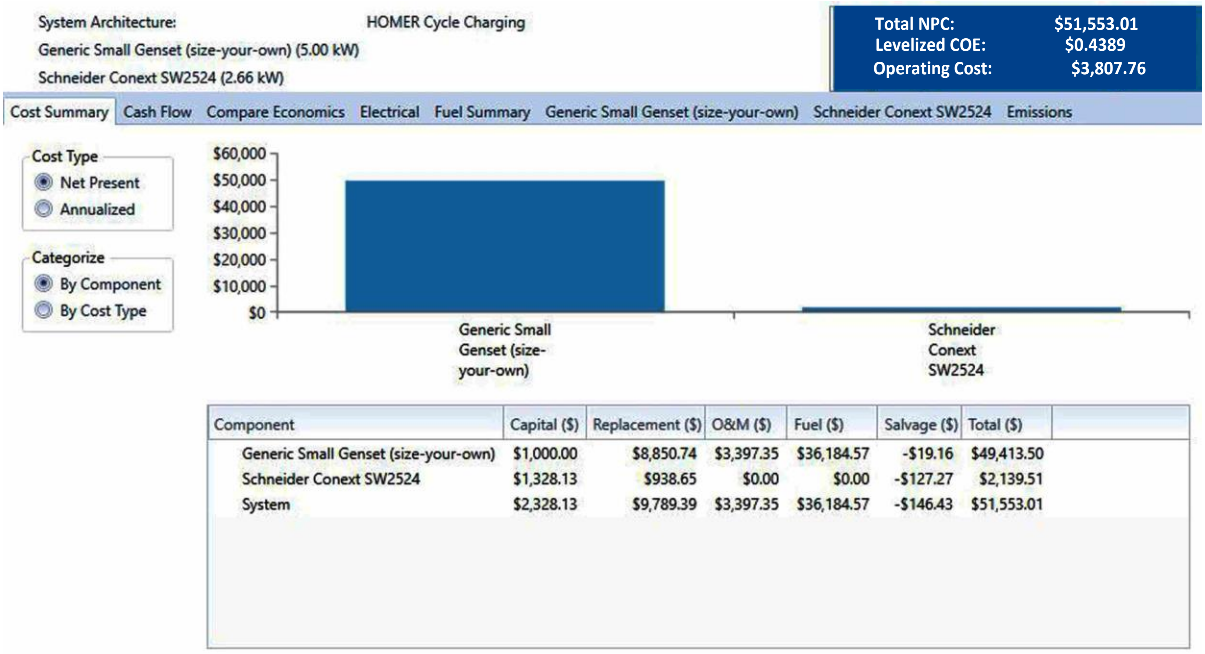


Fig. 13. Summary of the diesel generator only system cost results.

The value of electricity tariff and diesel fuel price in Libya are about $ 0.004/kWh and 0.11 $/L, respectively, which is considered among the world's cheapest rates [13]. So, the economic feasibility study in a standard way for RE projects to feed loads is considered extremely difficult due to the specificity of the Libyan situation. Subsidies for electric power and fuel are up to more than 11% of GDP [13-15]. Moreover, the lack of implementation of a Feed-in-Tariff (FiT) policy and the absence of incentives to support sustainable energy options are critical factors for comparing a RE source with the grid-connected option. However, the grid connection suffers from its unreliability and almost daily load shedding.

To calculate the PV energy system payback period, we calculate the total cost of installing PV minus the financial incentives that the state gives to support clean energy and divide it by the value of annual energy bills. The estimated NPC of the proposed PV-battery system is $42,892. There are no financial incentives to switch to solar energy in Libya, so the total cost of the system will not change. The electricity tariff in Libya of $0.004/kWh is much lower than that of the proposed PV-battery system COE reaching $0.365/kWh. It is clear that the proposed system is not economically feasible in its current form, compared with the grid option, but the grid is not available in Libya. The study was conducted to address power outages in homes connected to a grid. Also, to study the feasibility of using this technology as an alternative to energy sources used in rural areas, their loads are naturally much less than the house under study loads. Here are some important observations and recommendations:

- The battery bank is a key factor impacting the capital cost of isolated PV-battery systems. For this reason, it is necessary to decrease its size by reducing the demand load.

- Since heating and cooling loads represent 40% of the total household consumption [16], it's recommended to increase the insulation of homes by changing the construction technology currently used in Libya, which relies on cement bricks without any insulation.
- It is recommended to take advantage of the surplus produced electricity from the independent PV-battery system by selling it to the grid if this policy is adopted in the future.
- Giving the state incentives for RE projects - to reduce their costs - plays an essential role in motivating the Libyan population to switch to RE systems.

4. DYNAMIC MODELING, SIMULATION, AND THE RESULTS

The PV-battery system is greatly affected by changes in temperature and radiation, so the system's output has been correlated with a DC/DC boost converter with the maximum power point tracker (MPPT) controller. The perturbation and control method is implemented in this model to regulate the duty cycle of the algorithm of MPPT, which controls the output DC voltage to 48 V and supplies it to the load and battery bank. The battery bank will be out of use when the PV array production power is sufficient to meet the house load. Therefore, the battery bank's primary duty is feeding the loads during the night period and in cloudy weather. The proposed PV-battery system has been molded in the MATLAB /Simulink environment, as shown in Fig. 14.

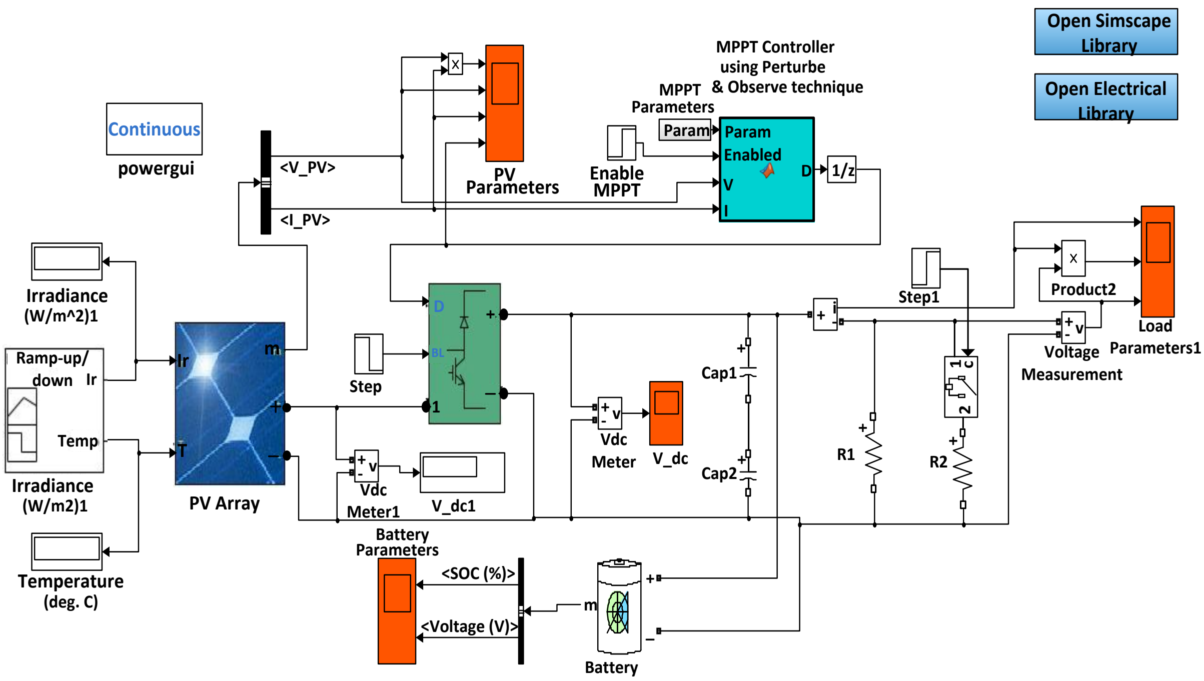


Fig. 14. MATLAB/Simulink model of the PV-battery system.

The house's load was divided to apply two scenarios on the proposed system to ensure its stability with various load demands. The system was connected with half of the load in the first situation and in the second one with a full load. Despite the difference in loading, the system's final desired output showed to be stable at 48 V DC voltage as revealed by Fig. 15.

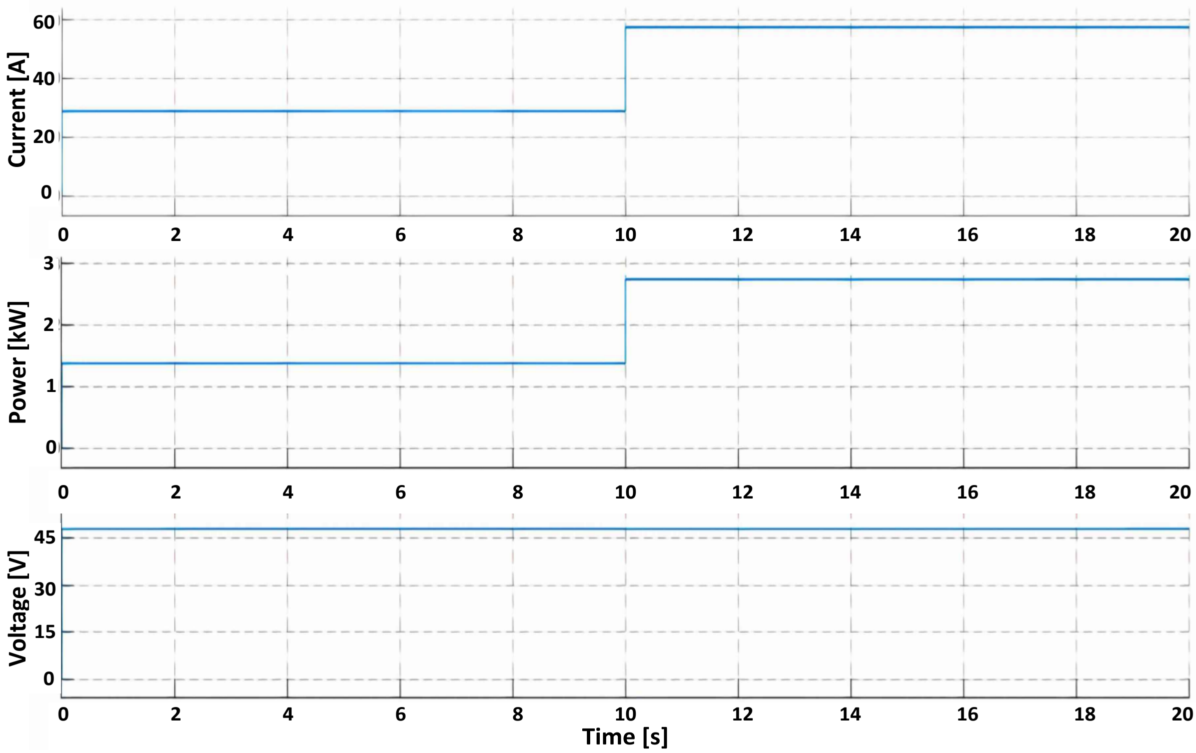


Fig. 15. The load voltage, current and power.

5. CONCLUSIONS

This study included real bills in calculating the load for a typical house in Benghazi, Libya. A 48 DC volts were used as a power supply, chosen after reviewing previous research related to the DC-only houses. Complete modeling, sizing, and optimization for the stand-alone PV-battery system with DC load have been presented in this paper. The performance of boost converter, MPPT controller and battery bank charging is evaluated under various solar irradiance. MPPT controller made significant improvements on PV array outputs, leading to the system's final desired output voltage of 48V DC with a stable operation. The results show that the system's initial capital cost is about $21,603. However, despite the proposed stand-alone PV system’s stability and its ability to fully meet the house load, it will not be economically feasible to apply this approach on houses with large loads within the electrical grid. In contrast, this technology is instrumental for Libya’s rural villages with basic electricity needs, where access to an electrical grid for these communities is unavailable or not cost-effective. Moreover, the proposed isolated PV-battery system compared to the diesel generator option is a more economical solution to feed residential loads mainly due to the severe damage to the grid infrastructure. Also, there is excess annual energy of 6,536 kWh that can be used in the future for an additional load.

Acknowledgment: The authors would like to thank Eng. Ahmed Ben Atia from the planning department/GECOL for providing the necessary load data for executing this research.

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