Journal of New Materials for Electrochemical Systems
Vol.25, No.2, April 2022 pp. 116-125
Journal homepage: http://iieta.org/journals/jnmes

Optimal configuration and techno-economic analysis of hybrid photovoltaic/PEM fuel cell power system

Hamza Bahri[1,2] and Abdelghani Harrag[2*], Hegazy Rezk[3,4]

[1]Electrical Engineering Department, Faculty of Technology, Mohamed Boudiaf University of Msila, 28000 Msila, Algeria
[2]Mechatronics Laboratory, Optics and Precision Mechanics Institute, Ferhat Abbas University Setif 1, Cite Maabouda (ex. Travaux), 19000 Setif Algeria
[3]College of Engineering at Wadi Addawaser, Prince Sattam Bin Abdulaziz University, Wadi Addawaser 11991, Saudi Arabia
[4]Electrical Engineering Department, Faculty of Engineering, Minia University, Minia 61517, Egypt

Corresponding Author Email: a.harrag@univ-setif.dz

https://doi.org/10.14447/jnmes.v25i2.a05

Received: November 17-2021
Accepted: May 5-2022

Keywords:
Photovoltaic, Fuel cell, Hydrogen, Electrolyzer, Battery, TNPC, COE, HOMER.

ABSTRACT

In this study, a renewable energy-based hybrid system was designed capable of meeting known electrical load requirements, as the system includes a combination of photovoltaic cells (PV), a fuel cell, batteries, an electrolyzer, and a hydrogen tank. This hybrid system supplies the cell tower located in the village of Ouanougha, country of Algeria with the annual electrical energy demand of 47 kWh/day. A Hybrid optimization model for electric renewable (HOMER) simulation software is utilized for modeling, optimize sizing, simulation as well as performing the techno-economic analysis of this hybrid system. HOMER software gives several optimum system configurations, which are compared among themselves for identifying the optimum system configuration. The comparison is based on the total net present cost (TNPC) and levelized cost of energy (LCOE). Other cost parameters can be provided such as initial capital cost, operation, and maintenance cost (O&M). The simulation result shows that, the proposed hybrid system has the lowest TNPC, LCOE and Initial capital, which are 64,384 $, 0.259 $/kWh and 35,850 $, respectively. On the other hand, it proved that the hybrid system is environmentally friendly and without producing any polluting gas. This paper also focuses on the operational strategy for feeding the load, as the results show that the hybrid system generally fulfills the requirements of the load.

1. INTRODUCTION

The depletion of fossil fuel resources in addition to an increase in the percentage of carbon dioxide emissions in nature causes global warming, which has led researchers to the necessity of a rapid trend towards benefiting from renewable energy resources [1]. This latter includes geothermal energy, wind, hydraulic, wave, biomass and solar energy are the ideal resources to make them alternatives to traditional energy systems based on fossil fuels. The solar energy source is one of the most common renewable energy sources because it is clean, non-depletable, freely available everywhere and it is an important source for the formation of other sources on earth [2]. To generate electricity from the solar energy source, photovoltaic (PV) modules technologies are used [3]. Photovoltaic systems have been used in many applications such as grid-Connected, water pumping, building integrated, spacecraft and electric vehicles [4], which has given a positive impact in social, economic, and environmental. However, when using PV systems only to feed the loads in some applications, the project demands a large number of panels to cover the load requirements, which requires a high investment cost. Therefore, it cannot be exploited as an energy source individually to feed the load due to the high investment costs as well as changes in operating conditions such as temperature and solar radiation that affect the value of the energy produced [5]. To beat this issue a new concept, namely Hybrid Energy Systems has emerged [6]. The hybrid system is defined as the combination of two kinds or more of renewable with non-renewable energy sources or without non-renewable energy sources and an optional storage system to exploit all the merits of these technologies to achieve better overall performance and to meet requirements load [7]. The selection of the application mode and the configuration of the hybrid system are based on several factors such as electrical grid availability, cost of grid supplied electricity, meteorological conditions (solar irradiation and wind speed), capacity, and requirement of load as well as the availability of the resources.

Hybrid systems based on renewable energy resources provide valuable benefits as they help reduce greenhouse gases, decrease the cost of energy, improving power quality and reliability, feasibility remote and rural areas electrification, improving services and creating new job opportunities [8]. So, it can be said that the hybrid system fulfills the three criteria for sustainable development, which include economic, environmental, and social aspects.

To exploit electricity generated from a renewable energy-based hybrid system with reliable performance and at a competitive economic price, the criteria for optimal component selection and design plays an important role. Hence, an optimum sizing method is essential for using the hybrid system with high efficiently and to guarantee the lowest investment [9] [10]. This type of optimization requires a detailed analysis from several aspects, especially the site, because of its various affects such as changes in climatic conditions and their relationship to the cost of the system as a whole [10]. For this reason, numerous software and optimization techniques have been reported in the literature. Genetic algorithm, particle swarm optimization and simulated annealing are the most optimization techniques for hybrid system sizing used in the literature, also techniques mentioned such as linear programming, evolutionary algorithms, neural networks, simplex algorithm, dynamic programming, stochastic approach, iterative and probabilistic approaches, design space based approach, parametric and numerical approaches, response surface methodology, matrix approach and quasi-Newton algorithm [11]. On the other hand, one of the most powerful sizing tools have been developed and widely utilized in many applications for hybrid systems is Hybrid Optimization Model for Electric Renewables (HOMER) software that was developed by National Renewable Energy Laboratory (NREL), United States [11].

Therefore, this paper shows a hybrid system composed of PV with FC. Often, we distinguish two cases in energy production from the PV system and the requirements of the load, there may be a surplus in energy production that corresponds to fewer requirements for the load, and therefore in such a case we resort to storage using batteries, also the production of hydrogen to feed the fuel cell by using an electrolyzer. The stored energy is used to supply the load in the event of a deficit in the PV system or an increase in the load requirements. To carry out the present study, in which collects the components of hybrid system into a single workable system, HOMER software has been employed. Similar to simulation, HOMER allows many tasks to be completed. It determines the best possible system doable configuration so that there is a match between supply and demand, optimization of the size of the hybrid system, provides the cost analysis for hybrid energy system, distribution the energy supplied to the components with best proper timings, calculates the energy efficiency of the whole system [12] [13].

The main purpose of this paper is to design and optimize a hybrid power system model that includes PV system and FC with metrological data inputs to feed the considered load. For this reason, this paper is organized as follows: The second section reviewed the literature published since the second half of the last decade. In the next section, which presents load demands, different component specifications and their economic data. Section 4, show the input data parameters based on LCOE, TNPC, LCC and salvage cost. Fifthly, the simulation and optimization results obtained with HOMER software are presented and discussed. Finally, paper concludes with a conclusion.

2. PREVIOUS LITERATURE

HOMER software helps for designing and analyzing the hybrid power systems to determine the best configuration from a group of optimized systems that fulfill the load demand under particular input parameters by performing a technical and economic analysis. Several renewable generators, conventional, storage components, electronic power devices and other inputs are modeled in HOMER such as PV array, Wind turbine, Fuel cell stack, Biomass, Hydropower, diesel generators, Electrical grid, Batteries bank, Electrolyzer, Hydrogen tank and DC/AC Converters. For this reason, HOMER can be applied for wide modes of system designs: whether stand-alone and grid connected modes. Many papers have been published assessing these hybrid systems using Homer. Table 1 shows a summary of the most relevant papers published. From this table we can observe the following:

- Several configurations have been studied and optimized through these papers, in which PV/Win/Diesel, PV/Diesel and PV/Win are the most configurations applicable as hybrid systems in remote areas, islands, villages, hotels, universities and residences.
- PV array is considered the most contributing source of all previous configurations.
- Converter and battery are among the key parts in a hybrid system configuration.

Optimization results for each configuration intended for feeding the load is based on the initial capital cost, Operating and maintenance (O&M), total net present cost (TNPC) and levelized cost of energy (LCOE). The best configuration presented by HOMER according to the minimum value of NPC and COE.

3. DESCRIPTION OF HYBRID SYSTEM COMPONENTS

In this section, we shall discuss the specifications of the different parts of this hybrid system shown in Figure 1, which six major components need to be designed: PV panel with battery, PEM fuel cell fed by an electrolyzer through hydrogen tank; inverter to fed load. To obtain the optimal and realistic result with the optimum configuration for these component sizes some economic inputs must be introduced.

3.1 Load demands of cell tower

For any power generating system, the load is an important part to define the optimal sizing of the system components. Some of these loads always need continuous feeding due to the services they provide. Undoubtedly, Communication technology systems are considered as a critical load due to the necessity to operate them day and night. Consequently, such loads require continuous service without interruption and high quality and reliability of electrical energy. In this study, a cell tower in the village of Ouanougha, the country of Algeria was selected to test the feasibility of the designed renewable energy-based hybrid system. The most important uses of electricity in this load are electronic components, Air conditioning, Lighting, signalization lamp, heater, and other equipment. Figure 2 illustrates the load profile of the cell tower. The average electricity consumption is 47 kW h/day with 5.4kW of peak demand.

Table 1: Description hybrid system in different articles.

Year	Article Number	Journal	Source							Converter		Storage	
			PV	Win	FC	Hydro	Biomass	Diesel	Electrical Grid	Converter	Electrolyzer	Battery	Hydrogen Tank
2015	[14]	R. E.	✓	✓	/	/	/	✓	/	✓	/	✓	/
	[15]	R. E.	✓	✓	/	✓	/	✓	/	✓	/	✓	/
	[16]	R. E.	✓	/	/	/	/	/	✓	✓	/	/	/
	[17]	R. E	✓	/	/	/	/	✓	/	✓	/	✓	/
	[18]	R. E	/	✓	✓	/	/	✓	/	✓	✓	/	✓
	[19]	R. E	/	✓	/	/	/	✓	/	/	/	/	/
	[20]	R. & S. E. Rev.	✓	✓	✓	/	/	✓	✓	✓	✓	✓	✓
	[21]	R. & S. E. Rev.	✓	/	/	/	/	✓	/	✓	/	✓	/
	[22]	R. & S. E. Rev.	✓	✓	/	/	/	/	✓	/	/	/	/
	[23]	R. & S. E. Rev.	✓	✓	/	✓	✓	✓	/	✓	/	✓	/
	[24]	E.	✓	✓	/	✓	/	✓	/	✓	/	✓	/
	[25]	E.	✓	/	/	/	/	✓	/	✓	/	✓	/
	[26]	E.	✓	/	/	/	/	✓	/	✓	/	✓	/
	[27]	I. J. H. E.	✓	✓	✓	/	/	✓	/	✓	✓	✓	✓
	[28]	A. E.	✓	/	/	/	/	✓	/	✓	/	✓	/
	[29]	E. C & M.	✓	✓	/	/	/	/	✓	✓	/	✓	/
	[30]	E. C & M.	✓	✓	/	/	/	✓	/	✓	/	✓	/
	[31]	S. E. T. & Ass.	✓	✓	/	/	/	✓	/	✓	/	✓	/
	[32]	IEEE	✓	✓	/	/	/	/	/	✓	/	✓	/
	[33]	IEEE	✓	✓	/	/	/	/	✓	✓	/	✓	/
2016	[34]	E	✓	/	✓	/	/	/	✓	✓	✓	✓	✓
	[35]	E. Rep.	✓	/	✓	/	✓	/	/	✓	✓	✓	✓
	[36]	Sus	✓	✓	/	/	/	/	/	✓	/	✓	/
	[37]	R. & S. E. Rev.	/	✓	/	/	/	✓	/	✓	/	✓	/
	[38]	R. E.	/	/	/	/	/	✓	/	✓	/	✓	/
	[39]	S. E. T. & Ass.	✓	✓	/	/	/	✓	/	✓	/	✓	/
2017	[40]	R. & S. E. Rev	✓	/	✓	/	/	✓	/	✓	✓	✓	✓
	[41]	IEEE	✓	✓	/	/	/	✓	✓	✓	/	✓	/
2018	[42]	J. E. & C. E.	✓	✓	✓	/	/	/	/	✓	✓	✓	✓
	[43]	IEEE	✓	/	/	/	/	/	✓	✓	/	/	/
	[44]	IEEE	✓	✓	/	/	/	✓	/	✓	/	✓	/
	[45]	IEEE	✓	/	/	/	/	/	✓	✓	/	/	/
	[46]	IEEE	✓	/	/	/	/	✓	✓	✓	/	/	/
2019	[47]	IEEE	✓	/	/	/	/	/	✓	✓	/	/	/
	[48]	IEEE	✓	/	/	/	/	✓	✓	✓	/	✓	/
	[49]	IEEE	✓	✓	/	/	/	✓	✓	✓	/	✓	/
	[50]	IEEE	✓	/	/	/	/	✓	✓	✓	/	/	/
	[51]	IEEE	✓	/	/	/	/	/	✓	✓	/	/	/
	[52]	IEEE	✓	/	/	/	/	✓	✓	✓	/	✓	/
	[53]	IEEE	✓	/	✓	/	/	/	/	✓	✓	✓	✓
2020	[54]	IEEE	✓	/	/	/	/	✓	✓	✓	/	/	/

3.2 Solar radiation and temperature

The solar radiation and temperature set databases were obtained from the PV-GIS. The latitude and longitude, 35°58 N and 4°11 E were considered in the HOMER software from which it received the radiation data. Figure 3 shows both solar radiation and temperature data for the studied site. From Figure 3, solar radiation ranges between 2360 kWh/m^2/day as minimum value registered in December and 7710 kWh/m^2/day as maximum value registered in June, which is high during the summer period and decreases during the winter period. The same applies to temperature values where the monthly average minimum is 5°C and the average maximum is 25°C.

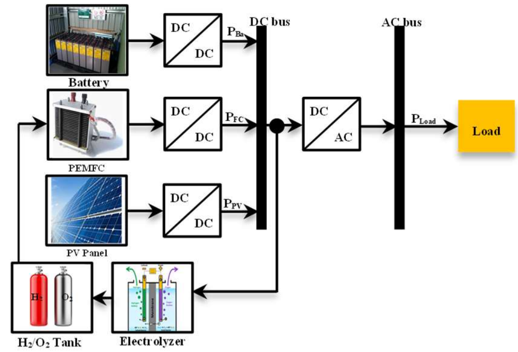

Figure 1: The configuration of the proposed system.

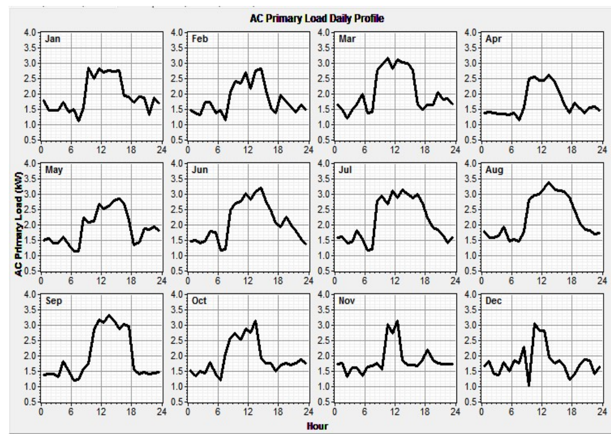

Figure 2: Average monthly load profile kW.

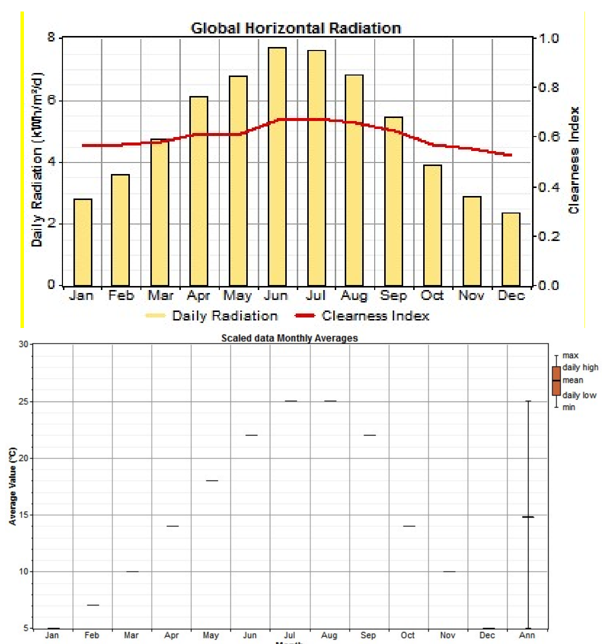

Figure 3: Monthly average of radiations and ambient temperatures.

3.3 Solar PV panels

Among all renewable energy sources available, the solar energy source is considered as the most renewable energy source prevalent. The technology of photovoltaic cells, which are used to harvest the sun's energy is constantly evolving and converting it into electrical energy. Mostly, the manufacturer specifies the life of the photovoltaic panels, which reaches 20 years. As for the cost, it is related to the value of the power produced in addition to the cost of installation, replacement, and a small amount of maintenance cost for the tracking system. According to [40], the cost of a peak 1kW produced from PV array reaches 1000$. Several parameters control the performance of photovoltaic cells such as technologies of fabrication (Mono-crystalline, Multi-crystalline and Amorphous Silicon), conditions climatic (irradiation and temperature), in addition to the site [55]. On the other hand, other factors must be taken into consideration, such as the ground reflectance of 20%, as well as the derating factor, which aims to reduce the electric production by 20% to approximate the changing impacts of temperature and dust on panels [40]. It should be noted that PV panels slope angle is set to 36° and 0° as array azimuth range, which refers to the parallel of latitude of the studied site and the south direction respectively.

3.4 Battery storage bank

The battery is essential in the hybrid system to store the excess power and after that used to ensure a continuous supply of energy to the load during the day or at night when the PV generators is unable to produce any power. Vision 6FM200D batteries were selected in this system. It is characterized by its terminal voltage 12V and 200 Ah capacity. As for the effect of temperature on batteries, the Homer software does not take it into account and that the battery maintains its characteristics throughout its estimated life of three years [56]. 600 $ is the total capital cost of each battery and 110 $ as the replacement cost, while the O&M needs only 10 $ [57]. This battery bank is built of 4 strings in parallel; each string includes 4 batteries connected in series. Therefore, the total numbers of batteries are 8 and the DC bus is 48 V.

3.5 Fuel Cell

A fuel cell is an electrochemical system based on converting chemical energy directly into electrical energy. Fuel cell contains several components, the main is the polymer electrolyte sandwiched between two terminals (anode and cathode) [58]. The anode and cathode are the site of the chemical reactions, while the polymer electrolyte only allowed particles to pass without the electrons [59]. In this way, the electrons resort to traveling through the outer circuit from the anode to the cathode to generate electrical energy. There are several types of fuel cells available in the market. Depending on the type of application fuel cell type can be chosen. Although there is no specific type of fuel cell can be simulated within HOMER software; hence, it has been looked at the budget range and the technical characteristics for the Proton Exchange Membrane Fuel Cell (PEMFC). This latter was assumed for this study which is suitable for small power applications. The total cost of PEMFC includes PEMFC himself with the auxiliary devices such as compressor, DC/DC converter ...etc. In this simulation, the capital cost varies 3000-6000 per Kw [60] [61]. While that the installation, replacement and operational Maintenance cost is estimated to be 3000 $, 2500 $ and 0.080 $/h, respectively [57]. On the other hand, the PEMFC lifetime was assumed would last 40,000 h, while the efficiency reaches at 50% [57]. The operating mode of PEM fuel cell is presented in Figure 4, The PEMFC forced on from 18:00 in the evening until 7:00 in the morning during the months of May, Jun, July, and August, while it is forced on from17:00 until 8:00 for the rest of the months.

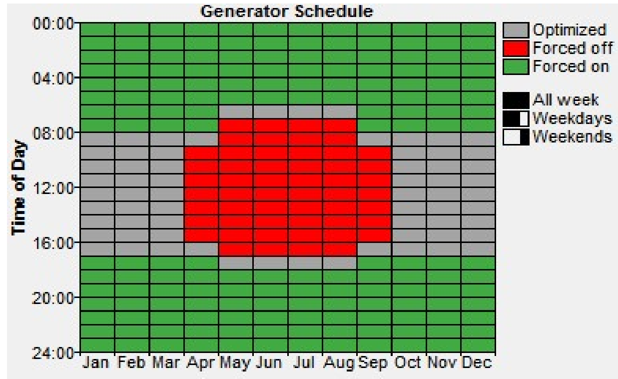

Figure 4: The operating mode of PEMFC.

3.6 Electrolyzer system

Hydrogen is the simplest chemical element in the universe where the hydrogen atom consists of only a proton and an electron, making it the lightest element. In addition, it is considered the most abundant element in the universe, making up more than 90% of all known matter [62]. Water is one of the elements that contain the hydrogen and oxygen necessary to operate a fuel cell. The water electrolysis process is used to separate water molecules and produce hydrogen by using the electrolyzer device [63]. The latter converts DC electrical energy into chemical energy stored in hydrogen [64]. The net volume of hydrogen produced is directly proportional to the electrolyzing current and number of electrolyzers connected in series. Between 1500-3000 is cost of the electrolyzer per kW [57]. The installation cost 1500$/kW, replacement cost 1000$/kW and annual O&M cost 5$/yr is considered. The efficiency and lifetime are considered 80% and 20 years respectively.

3.7 Hydrogen tank

PEMFC operates at night and requires the hydrogen produced by the electrolyzer throughout the day and therefore it must be stored for later use. There are several storage techniques used for hydrogen out of which the most is to store it as a compressed gas in tanks or as a metal hydride [65]. According to [61], the price of hydrogen related to the size of the hydrogen tank, which is estimated to be 1200 $ per 1kg of hydrogen.

3.8 Converter

The output power of hybrid system PV, FC, and battery in form DC, while the load is AC based. Thus, the insertion of an inverter between source and load is a prerequisite for the DC to AC power conversion. According to the output power of the hybrid system sources, HOMER software sizes the inverter. The latter is characterized by it efficiency which reaches 90% with a lifetime is up to 15 years [66]. The capital and replacement cost per kilowatt of inverter are considered 800 $ and 750 $ respectively [67]. Meanwhile, the O&M cost for converter DC/AC is zero.

4. ECONOMIC PARAMETER

The development of any hybrid system basically needs strong economic support. HOMER software is used as a tool to find the optimal sizing and perform techno-economic analysis of the system. The economic analysis is a crucial part to determine the optimum system; it can be performed based on different parameters. LCOE, TNPC, LCC and salvage cost are considered the four main economical parameters that need to be identified in the analysis. The detail for each parameter is mentioned in[34].

5. OPTIMIZATION RESULTS FOR HYBRID SYSTEM

PV panel is considered as the primary source of the hybrid system. The excess electricity produced from the PV system can be stored in the battery. This latter, helps the improving the hybrid system's efficiency, reduce the amount of unused electricity and provide security for the energy supply. The PEMFC source has an electrolyzer and tank to produce hydrogen and store it. The inverter is added to the system to feed load by AC energy. The schematic diagram of the system hybrid using HOMER software is shown in Figure 5.

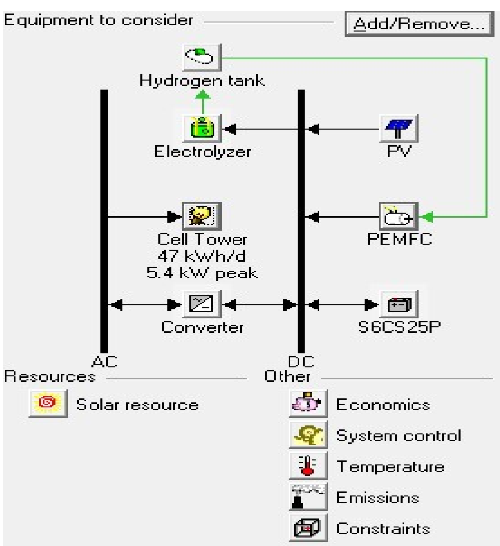

Figure 5: Schematic diagram of hybrid system.

Table 2 represents the top seven optimization results given by HOMER software based on the design specifications for this hybrid system. The NPC and COE are considered as the most important decision-making parameters to choose the best system. As it is shown in this table, system number one is the best system compared to the other systems, which has Initial capital of 35,850 $, TNPC is 64,384 $ and COE is 0.259 $/kWh. Also, the value of the operating cost is 1.974 $/y and the maximum capacity shortage is considered 5% of the total load.

Table 2: Optimization results for PV, Battery and PEMFC based system

Sensitivity Results | Optimization Results

Double click on a system below for simulation results.

PV (kW)	PEMFC (kW)	6FM200D	Conv. (kW)	Elec. (kW)	H2 Tank (kg)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Capacity Shortage
12	7	8	7.0	5	2	$ 35,850	1,974	$ 64,384	0.259	0.05
10	7	12	7.0	5	2	$ 36,250	1,949	$ 64,419	0.259	0.05
12	7	8	7.0	5	3	$ 36,850	1,967	$ 65,281	0.262	0.04
10	7	12	7.0	5	3	$ 37,250	1,942	$ 65,324	0.263	0.04
12	7	8	8.0	5	2	$ 36,650	1,984	$ 65,333	0.263	0.04
10	7	12	8.0	5	2	$ 37,050	1,959	$ 65,368	0.263	0.05
10	7	16	6.0	5	1	$ 36,850	1,989	$ 65,593	0.264	0.05
12	7	12	6.0	5	1	$ 36,450	2,021	$ 65,668	0.264	0.04
10	7	16	6.0	5	2	$ 37,850	1,962	$ 66,216	0.266	0.04
12	7	8	7.0	5	4	$ 37,850	1,963	$ 66,228	0.266	0.04
12	7	8	8.0	5	3	$ 37,650	1,977	$ 66,230	0.266	0.04
12	7	12	6.0	5	2	$ 37,450	1,993	$ 66,257	0.266	0.03
10	7	12	8.0	5	3	$ 38,050	1,953	$ 66,273	0.267	0.04
10	7	12	7.0	5	4	$ 38,250	1,940	$ 66,293	0.267	0.04
10	7	16	7.0	5	1	$ 37,650	1,999	$ 66,542	0.268	0.04
12	7	12	6.0	5	1	$ 36,450	2,086	$ 66,607	0.268	0.04
12	7	12	7.0	5	1	$ 37,250	2,032	$ 66,617	0.267	0.03
10	7	16	6.0	5	1	$ 36,850	2,073	$ 66,811	0.269	0.05
12	7	8	7.0	6	3	$ 38,100	1,994	$ 66,918	0.269	0.05
10	7	16	6.0	5	3	$ 38,850	1,958	$ 67,153	0.270	0.04
12	7	12	6.0	5	3	$ 38,450	1,986	$ 67,159	0.270	0.03
10	7	16	7.0	5	2	$ 38,650	1,973	$ 67,165	0.270	0.03
12	7	8	8.0	5	4	$ 38,650	1,974	$ 67,177	0.270	0.04
12	7	12	7.0	5	2	$ 38,250	2,003	$ 67,206	0.270	0.02
12	7	12	6.0	5	2	$ 37,450	2,060	$ 67,231	0.270	0.04
10	7	12	8.0	5	4	$ 39,050	1,950	$ 67,242	0.271	0.04

When we look at the net present cost of the hybrid system, it includes three parameters capital cost, replacement, and O&M. From Table 3, it can be observed that capital cost presents the highest, and then it comes second the operating and maintenance cost of the system and finally the replacement cost. In the capital cost, PV and battery is highest, while PEMFC to a lesser degree. This latter has the highest replacement cost. The O&M cost of the system is also expensive, in which the highest value is for both PEMFC and PV respectively.

Table 3: Cost detail of the PV, Battery and PEMFC based system

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	12,00	3,320	8,672	0	-1,975	22,018
PEMFC	4,200	5,542	8,879	0	-627	17,994
Battery	4,800	1,514	1,156	0	-8	7,462
Converter	5,600	2,075	202	0	-1,234	6,643
Electrolyzer	6,250	1,647	301	0	-979	7,219
Hydrogen Tank	2,000	0	48	0	0	2,048
Other	1,000	0	0	0	0	1,000
System	35,850	14,098	19,260	0	-4,824	64,384

Table 4 shows details electrical power generation from the hybrid source and consumption of load. An Analysis of this data shows that the PV array dominates the power generation by providing 69% of the total generated power, followed by then PEMFC by providing power at 31%. The reason for this is due to the largest consumption of load during day, whereas the PEMFC used at night for operating strategy and the high cost of energy of hydrogen-based system.

Table 4: Total production and consumption of system

Production output (kWh/yr)			
PV array	PEMFC	Battery Annual Throughput	Total Production
19,235	8,498	1,165	27,733
69%	31%	-	100%
System parameters (kWh/yr)			
Load consumption	Excess Electricity	Unmet Electric Load	Capacity Shortage
17,207	2,138	57.8	781
73 %	7.71 %	0.33 %	4.52 %

The analyzing consumption of electrical power in hybrid system is divided into cell tower load and the electrolyzer, in which reaches at 23,431 kWh/yr. The cell tower load consumes 17,207 kWh/yr, which represents 73% of total consumption, while the electrolyzer consumes 6,225 kWh/yr, with percentage is 27%. In fact, not all of the energy produced from PV is consumed. There is an excess of energy estimated at 2,138 kWh/year. On the other hand, the electricity shortage is only 5% of the total load which means the system can supply almost the whole load demand.

The operation of a PEM fuel cell depends on the availability of hydrogen produced by the electrolyzer. The Figure 6 shows the hydrogen produced over a year. Total hydrogen production is 126 kg/year where the daily production fluctuates between 0.15 kg/day to 0.45 kg/day. This fluctuation of production is due to the availability of electricity to the electrolyzer through PV or sometimes Battery bank. The generated hydrogen during day is stored in the hydrogen tank. The hydrogen storage level depends on the electrolyzer and PEMFC operation.

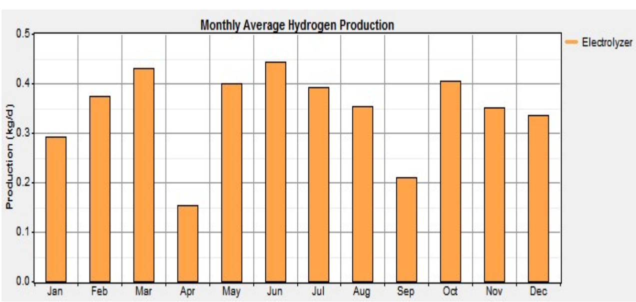

Figure 6: Hydrogen production by electrolyzer

6. POWER OUTPUT HOURLY DATA

In the proposed HRES, PV/PEMFC energy sources with storage units are integrated to feed cell tower. In such HRES the control strategy of energy management between sources is important part, as several aspects are taken into account such as: selection of the optimal approach, minimum operating costs and components life. The control strategy determines how to manage power and to make coordination between the different sources, i.e., determines the components must work and which not, where must one store energy surplus. The excess energy produced from PV panel is exploited to charge the batteries or to feed the electrolyzer or other auxiliary components. According to the operating system situation, the battery bank will import (the battery is considered as a load), export (the battery is considered as a source) the necessary power. In which, if the power requested from load less than power produced by the PV source and the battery charging status (SOC), is maximum, then the excess power produced by the PV sources is directed to feed the electrolyzer, and the hydrogen produced is stored in the tank for later use by PEMFC. Likewise, when the battery's (SOC), is minimum.

The hourly data analysis of the HOMER software allows analysis of detailed simulation results in a variety of way to have a better understanding of the system operation strategy. Therefore, the demand load profile, power flow by each source PV/PEMFC, electrolyzer input, battery input/output power and battery state of charge are shown in Figures 7 to 9, during 24 hours.

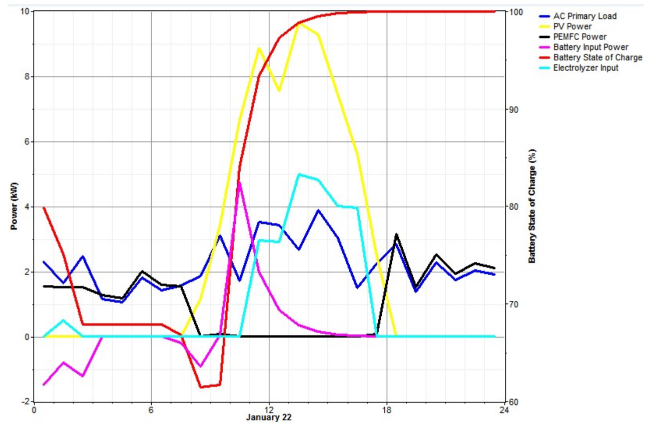

Figure 7: Operational conditions of PV, Battery and PEMFC hybrid system

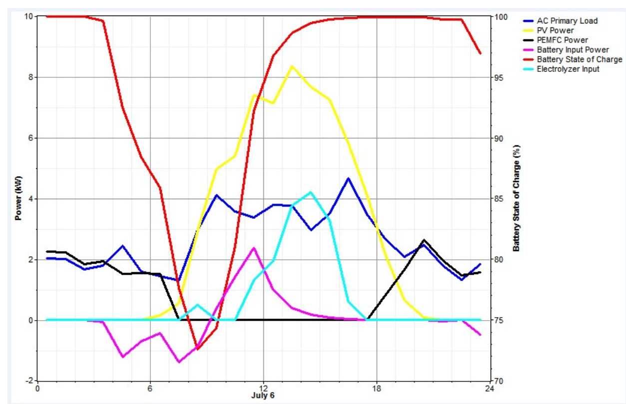

Figure 8: Operational conditions of PV, Battery and PEMFC hybrid system

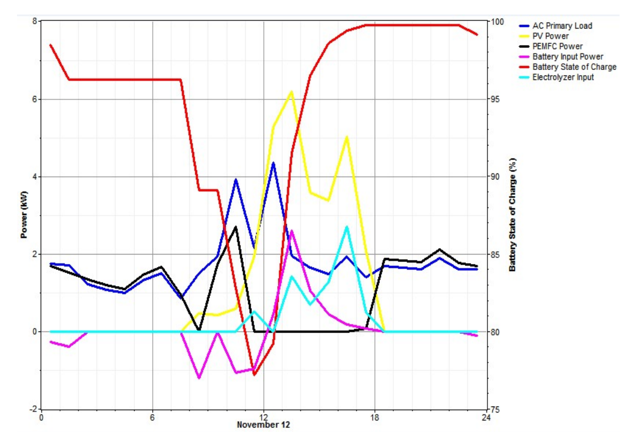

Figure 9: Operational conditions of PV, Battery and PEMFC hybrid system

In the case of January, from midnight until about 8 a.m. and from 17 in the evening until midnight corresponding to the hours when solar radiation is decreasing or absent, the cell tower is fed by a PEMFC with a battery bank. With the beginning of the morning period, the output energy of the PEMFC decreases until it becomes zero according to the specific strategy for it operating, while the PV array begins to deliver electrical energy with the increase of solar radiation starting from 7:30 a.m.; However, the output power is insufficient to cover the load requirements during these first hours, as the battery bank continues to feed the load as long as the SOC of battery is above 40%. With the increase in solar radiation, the output power of the PV array increases until it reaches maximum values during the middle of the day, exceeding 9 kW, as the excess energy is exploited to charge the battery as well as to feed the electrolyzer. The same process can be seen for the month of July with some differences related to weather conditions and changes in the strategy of the PEMFC work.

The case of November indicates to the decrease and fluctuations in the power production from PV system due to the decrease in the solar radiation, which leads to an inability to meet the requirements of cell tower during 7 a.m. until 12 p.m. During this period, the PEMFC and battery are assured the load requirements. Solar radiation returns to the rise after 12 p.m., as the photovoltaic arrays produce energy to feed the load with the possibility of supplying the electrolyzer and charging the battery until 18 p.m. During the evening, the requirements of the cell tower are guaranteed by PEMFC without any shortage. Generally, the total Unmet Electric Load reaches at 57.8 kWh/yr as presented in Table 4, this value is considered reasonable and very small.

7. CONCLUSION

In this study, an independent energy system based on renewable energy sources was proposed, which included both photovoltaic and fuel cells in addition to batteries as a storage system to satisfy the requirements of the cell tower. Using HOMER with all data input and designed load profile, a techno-economic analysis of a hybrid PV/PEMFC based system was performed with the study of optimum energy management between sources and load. The results of simulation prove the possibility of installing PV/PEMFC based system with battery and hydrogen as storage components for distributed generation of electric power for stand-alone applications at cell tower, in which the optimization sizing for hybrid system includes of 12 kW for PV array, 7 kW for PEMFC as well as 8 batteries. From the economic side, the major parameter of the study was TNPC and COE. Among other costs initial cost, replacement cost and O&M cost are considered. Power generation fees of the hybrid system has been found to be 0.259 ($/kWh) and total NPC 64,384 ($). On the other hand, this hybrid system gave many benefits, the most important of which is the possibility of using renewable systems as alternatives to traditional systems in these areas or for such loads, as they are reliable sources to meet the requirements of pregnancy and are environmentally friendly.

ACKNOWLEDGMENT

The Algerian Ministry of Higher Education and Scientific Research supported this research (Research PRFU Project A01L07UN190120180005).

NOMENCLATURE

Acronyms	Description
PV	Photovoltaic
FC	Fuel Cell
PEMFC	Proton Exchange Membrane Fuel Cell
Win	Wind
NREL	National Renewable Energy Laboratory
LCOE	Levelized Cost of Energy
TNPC	Total Net Present Cost
LCC	Life Cycle Cost
DC	Direct Current
R. E.	Renewable Energy
R. & S. E. Rev.	Renewable and Sustainable Energy Reviews
E.	Energy
I. J. H. E.	International Journal of Hydrogen Energy
A. E.	Applied Energy.
E. C & M.	Energy Conversion and Management
S. E. T. & Ass.	Sustainable Energy Technologies and Assessments
E. Rep.	Energy Reports.
Sus	Sustainability.
J. E. & C. E	Journal of Electrical and Computer Engineering.

REFERENCES

[1] R. Garraoui, M. Ben Hamed, L. Sbita ‘’A Robust Optimization Technique Based on First Order Sliding Mode Approach for Photovoltaic Power Systems’’ International Journal of Automation and Computing, 2015, Vol 6, P 620-629

[2] N. Harrabi, M. Souissi, A. Aitouche, M. Chaabane ‘’ Modeling and control of photovoltaic and fuel cell based alternative power systems’’ International journal of hydrogen energy, 2018, Vol 43, P 11442-11451

[3] A. Mohammedi, N. Mezzai, D. Rekioua, T. Rekioua ‘’ Impact of shadow on the performances of a domestic photovoltaic pumping system incorporating an MPPT control: A case study in Bejaia, North Algeria’’ Energy Conversion and Management, 2014, Vol 84, P 20-29

[4] N. Shankarappa, M. Ahmed, N. Shashikiran, Dr. H. Naganagouda ‘’ Solar Photovoltaic Systems– Applications & Configurations’’ IRJET, 2017, Vol 4, P 1851-1855

[5] K. S. Krishna, K. S. Kumar ‘’A review on hybrid renewable energy systems’’ Renewable and Sustainable Energy Reviews, 2015, Vol 52, P 907-916

[6] S. Bahramara, F. Jafari, A. Rahimi-Kian, H. Lesani ‘’Planning of a grid-connected smart micro-power system’’ In: Proceedings of the 2012 IEEE innovative smart grid technologies-Asia (ISGTAsia), 2012, P 1-5.

[7] A. R. Ghahnavieh, S. A. Nowdeh ‘’ Optimal PV–FC hybrid system operation considering reliability’’ Electrical Power and Energy Systems; 2014, Vol 60, P 325-333

[8] H. Sharma, S. Mishra ''Hybrid Optimization Model for Smart Grid Distributed Generation Using HOMER'' 2019 3rd International Conference on Recent Developments in Control, Automation & Power Engineering (RDCAPE), Noida, India, 2019, pp. 94-99, 2019, P 94-99, doi:10.1109/RDCAPE47089.2019.8979121

[9] P. Yilmaza, M. H. Hocaoglub, A. E. S. Konukman '' A pre-feasibility case study on integrated resource planning including renewables'' Energy Policy, 2008, Vol 36, P 1223-1232

[10] W. Zhou, C. Lou, Z. Li, L. Lu, H. Yang ''Current status of research on optimum sizing of stand-alone hybrid solar–wind power generation systems'' Applied Energy, 2010, Vol 87, P 380-389

[11] O. Erdinc, M. Uzunoglu ''Optimum design of hybrid renewable energy systems: Overview of different approaches'' Renewable and Sustainable Energy Reviews, 2012, Vol 16, P 1412-1425

[12] D. L. Kumar, B. B. Dash, A. K. Akella ''Optimization of PV/Wind/Micro-Hydro/Diesel Hybrid Power System in HOMER for the Study Area" International Journal on Electrical Engineering and Informatics, 2011, Vol 3, P 307- 325

[13] K. E. Okedu, R. Uhunmwangho ''Optimization of Renewable Energy Efficiency using HOMER" International Journal of Renewable Energy Research, 2014, Vol. 4, P 421-427

[14] S. C. Bhattacharyya '' Mini-grid based electrification in Bangladesh: technical configuration and business analysis'' Renewable Energy, 2015, Vol 75, P 745-761.

[15] Z. Chmiel, S. C. Bhattacharyya ''Analysis of off-grid electricity system at Isle of Eigg (Scotland): lessons for developing countries'' Renewable Energy, 2015, Vol 81, P 578-588.

[16] M. A. M. Ramli, A. Hiendro, K. Sedraoui, S. Twaha ''Optimal sizing of gridconnected photovoltaic energy system in Saudi Arabia'' Renewable Energy, 2015, Vol 75, P 489-495.

[17] M. A. M. Ramli, A. Hiendro, S. Twaha ''Economic analysis of PV/diesel hybrid system with flywheel energy storage'' Renewable Energy, 2015, Vol 78, P 398-405.

[18] D. Chade, T. Miklis, D. Dvorak ''Feasibility study of wind-to-hydrogen system for Arctic remote locations – Grimsey island case study'' Renewable Energy, 2015, Vol 76, P 204-211.

[19] M. Mudasser, E. K. Yiridoe, K. Corscadden ''Cost-benefit analysis of gridconnected wind–biogas hybrid energy production, by turbine capacity and site'' Renewable Energy, 2015, Vol 80, P 573-582.

[20] W. M. Amutha, V. Rajini ''Techno-economic evaluation of various hybrid power systems for rural telecom'' Renewable Sustainable Energy Review, 2015, Vol 43, P 553-561.

[21] H. Rezzouk, A. Mellit ''Feasibility study and sensitivity analysis of a stand-alone photovoltaic–diesel-battery hybrid energy system in the north of Algeria'' Renewable Sustainable Energy Review, 2015, Vol 43, P 1134-1150.

[22] D. S. Koussa, M. Koussa ''A feasibility and cost benefit prospection of grid connected hybrid power system (wind–photovoltaic) - case study: an Algerian coastal site'' Renewable Sustainable Energy Review, 2015, Vol 50, P 628-642.

[23] A. Chauhan, R.P. Saini ''Renewable energy based off-grid rural electrification in Uttarakhand state of India: technology options, modelling method, barriers and recommendations'' Renewable Sustainable Energy Review, 2015, Vol 51, P 662-681.

[24] M. R. Basir Khan, R. Jidin, J. Pasupuleti, S. A. Shaaya ''Optimal combination of solar, wind, micro-hydro and diesel systems based on actual seasonal load profiles for a resort island in the South China Sea'' Energy, 2015, Vol 82, P 80-97.

[25] K. Y. Lau, C. W. Tan, A. H. M. Yatim ''Photovoltaic systems for Malaysian islands: effects of interest rates, diesel prices and load sizes'' Energy, 2015, Vol 83, P 204-216.

[26] E. U. Khan, A. R. Martin ''Optimization of hybrid renewable energy polygeneration system with membrane distillation for rural households in Bangladesh'' Energy, 2015, Vol 93, P 1116-1127.

[27] Y. Kalinci, A. Hepbasli, I. Dincer ''Techno-economic analysis of a stand-alone hybrid renewable energy system with hydrogen production and storage options'' International Journal of Hydrogen Energy, 2015, Vol 40, P 7652-7664.

[28] E. Hurtado, E. Peñalvo-López, A. Pérez-Navarro, C. Vargas, D. Alfonso ''Optimization of a hybrid renewable system for high feasibility application in non connected zones'' Applied Energy 2015, Vol 155, P 308-314.

[29] S. Bhattacharjee, S. Acharya ''PV-wind hybrid power option for a low wind topography'' Energy Conversion and Management, 2015, Vol 89, P 942-954.

[30] F. Baghdadi, K. Mohammedi, S. Diaf, O. Behar ''Feasibility study and energy conversion analysis of stand-alone hybrid renewable energy system'' Energy Conversion and Management, 2015, Vol 105, P 471-419.

[31] M. L. Kolhe, K. M. I. U. Ranaweera, A. G. B. S. Gunawardana ''Techno-economic sizing of off-grid hybrid renewable energy system for rural electrification in Sri Lanka'' Sustainable Energy Technology Assessment, 2015, Vol 11, P 53-64.

[32] B, F. Ronad, S. H. Jangamshetti '' Optimal Cost Analysis of Wind-Solar Hybrid System Powered AC and DC Irrigation Pumps using HOMER'' 2015 International Conference on Renewable Energy Research and Applications (ICRERA), Palermo, Italy, 2015, P 1038-1042, doi: 10.1109/ICRERA.2015.7418568.

[33] Md. Nurunnabi, N. K. Roy '' Grid Connected Hybrid Power System Design Using HOMER'' 2015 International Conference on Advances in Electrical Engineering (ICAEE), Dhaka, Bangladesh, 2015, P 18-21, doi: 10.1109/ICAEE.2015.7506786.

[34] N. Mat Isa, H. S. Das, C. W. Tan, A. H. M. Yatim, K. Y. Lau '' A techno-e conomic ass essment of a combined heat and power photovoltaic/fuel cell/battery energ y system in Malaysia hospital'' Energy, 2016, Vol 112; P 75-90.

[35] A. Singh, P. Baredar '' Techno-economic assessment of a solar PV, fuel cell, and biomass gasifier hybrid energy system'' Energy Reports , 2016, Vol 2, P 254-260.

[36] H. Kim, S. Baek, K. H. Choi, D. Kim, S. Lee, D. Kim, H. J. Chang ‘’ Comparative Analysis of On- and Off-Grid Electrification: The Case of Two South Korean Islands’’ Sustainability, 2016, Vol 8, P 1-13, doi:10.3390/su8040350.

[37] P. R. Bhattarai, S. Thompson ‘’Optimizing an off-grid electrical system in Brochet, Manitoba, Canada’’ Renewable Sustainable Energy Reviews, 2016, Vol 53, P 709-719.

[38] S. Sarker ‘’Feasibility analysis of a renewable hybrid energy system with producer gas generator fulfilling remote household electricity demand in Southern Norway’’ Renewable Energy, 2016, Vol 87(Part 1), p 772-781.

[39] L. Olatomiwa, S. Mekhilef, O. S. Ohunakin ‘’Hybrid renewable power supply for rural health clinics (RHC) in six geo-political zones of Nigeria’’ Sustainable Energy, Technologies and Assessments, 2016, Vol 13, P 1-12.

[40] H. S. Das, C. W. Tan, A. H. M. Yatim, K. Y. Lau ‘’ Feasibility analysis of hybrid photovoltaic/battery/fuel cell energy system for an indigenous residence in East Malaysia’’ Renewable and Sustainable Energy Reviews, 2017, Vol 76, P 1332-1347.

[41] S. Ghose, A. El Shahat, R. J. Haddad ‘’ Wind-Solar Hybrid Power System Cost Analysis using HOMER for Statesboro,Georgia’’ Southeast Conference 2017, Charlotte, NC, 2017, P 1-3, doi: 10.1109/SECON.2017.7925324.

[42] M. H. Kebede, G. B. Beyene ‘’ Feasibility Study of PV-Wind-Fuel Cell Hybrid Power System for Electrification of a Rural Village in Ethiopia’’ Journal of Electrical and Computer Engineering, 2018, P 1-9, doi.org/10.1155/2018/4015354.

[43] M. Morad, M. Nayel, A. A. Elbaset, A. I. A. Galal "Sizing and Analysis of Grid-Connected Microgrid System for Assiut University Using HOMER Software" 2018 Twentieth International Middle East Power Systems Conference (MEPCON), Cairo, Egypt, 2018, P 694-699, doi: 10.1109/MEPCON.2018.8635166.

[44] S. Vendoti, M. Muralidhar, R. Kiranmayi "HOMER Based Optimization of Solar-Wind-Diesel Hybrid System for Electrification in a Rural Village" 2018 International Conference on Computer Communication and Informatics (ICCCI), Coimbatore, India, 2018, P 1-6, doi: 10.1109/ICCCI.2018.8441517.

[45] N. Pawar, P. Nema "Techno-Economic Performance Analysis of Grid Connected PV Solar Power Generation System Using HOMER Software" 2018 IEEE International Conference on Computational Intelligence and Computing Research (ICCIC), Madurai, India, 2018, P 1-5, doi: 10.1109/ICCIC.2018.8782411.

[46] A. Rajani, R. Darussalam, R. I. Pramana, A. Santosa "Simulation of PV - Biogas Integration on Hybrid Power Plant using HOMER: Study Case of Superior Livestock Breeding Center and Forage of Animal Feed (BBPTU - HPT) Baturraden" 2018 International Conference on Sustainable Energy Engineering and Application (ICSEEA), Tangerang, Indonesia, 2018, P 69-74, doi: 10.1109/ICSEEA.2018.8627132.

[47] A. Khan, K. B. Rana "Techno-Economic Analysis of 100 kW Rooftop Photovoltaic Grid - Type System Based on Actual Performance through Homer Software" 2019 International Conference on Issues and Challenges in Intelligent Computing Techniques (ICICT), Ghaziabad, India, 2019, P 1-5, doi: 10.1109/ICICT46931.2019.8977701.

[48] H. Sharma, S. Mishra "Hybrid Optimization Model for Smart Grid Distributed Generation Using HOMER" 2019 3rd International Conference on Recent Developments in Control, Automation & Power Engineering (RDCAPE), Noida, India, 2019, P 94-99, doi: 10.1109/RDCAPE47089.2019.8979121.

[49] V. B. Mary, I. W. Christopher, G. Themozhi "RHES-Economic Analysis and Power Management for a Technical Institution Using Homer" 2019 Fifth International Conference on Electrical Energy Systems (ICEES), Chennai, India, 2019, P 1-6, doi: 10.1109/ICEES.2019.8719307.

[50] V. Makwana, C. Kotwal, K. Arora "Optimum Sharing of Solar Power and Grid for an Academic Institute using HOMER," 2019 IEEE 5th International Conference for Convergence in Technology (I2CT), Bombay, India, 2019, P 1-5, doi: 10.1109/I2CT45611.2019.9033648.

[51] S. Kumar, P. Upadhyaya, A. Kumar "Performance Analysis of Solar Energy Harnessing System Using Homer Energy Software and PV Syst Software" 2019 2nd International Conference on Power Energy, Environment and Intelligent Control (PEEIC), Greater Noida, India, 2019, P 156-159, doi: 10.1109/PEEIC47157.2019.8976665.

[52] N. Shilpa, H. R. Sridevi "Optimum design of Rooftop PV System for An Education Campus Using HOMER" 2019 Global Conference for Advancement in Technology (GCAT), Bangalore, India, 2019, P 1-4, doi: 10.1109/GCAT47503.2019.8978446.

[53] A. Gougui, A. Djafour, D. M. Bilal, N. Khalfaoui, R. Youssef "Techno-economic Analysis and Feasibility Study of a Hybrid Photovoltaic/Fuel Cell Power System" 2019 1st International Conference on Sustainable Renewable Energy Systems and Applications (ICSRESA), Tebessa, Algeria, 2019, P 1-5, doi: 10.1109/ICSRESA49121.2019.9182415.

[54] J. Nikhilesh, S. B. Singh "Homer Based: A Real Time Case Study on Optimization and Simulation of Hybrid Energy System at NIT Kurukshetra and the Effect on the Environment" 2020 First IEEE International Conference on Measurement, Instrumentation, Control and Automation (ICMICA), Kurukshetra, India, 2020, P 1-5, doi: 10.1109/ICMICA48462.2020.9242814.

[55] A. Bai, J. Popp, P. Balogh, Z. Gabnai, B. Pályi, I. Farkas, G. Pintér, H. Zsiborács ‘’Technical and economic effects of cooling of monocrystalline photovoltaic modules under Hungarian conditions’’ Renewable and Sustainable Energy Reviews, 2016, Vol 60, P 1086-1099

[56] T. Lambert, P. Gilman, P. Lilienthal ‘’Micropower system modeling with HOMER’’ Integration of Alternative Sources of Energy, 2006, P 379-418

[57] M. H. Ashourian, S. M. Cherati, A. A. M. Zin, N. Niknam, A. S. Mokhtar, M. Anwari ‘’Optimal green energy management for island resorts in Malaysia’’ Renewable Energy, 2013, Vol 51, P 36-45.

[58] M. Díaz, A. Ortiz, I. Ortiz ‘’ Progress in the use of ionic liquids as electrolyte membranes in fuel cells’’ Journal of Membrane Science, 2014, Vol 469, P 379-396

[59] A. Beicha '' Modeling and simulation of proton exchange membrane fuel cell systems'' Journal of Power Sources, 2012, Vol 205, P 335–339

[60] O. H. Mohammed, Y. Amirat, M. Benbouzid, A. A. Elbaset ''Optimal design of a PV/fuel cell hybrid power system for the city of Brest in France'' IEEE international conference on green energy, 2014, P 119-123

[61] M. I. Normazlina, H. S. Das, C. W. Tan, A. H. M. Yatim, K. Y. Lau ''A techno-economic assessment of a combined heat and power photovoltaic/fuel cell/battery energy system in Malaysia hospital'' Energy, 2016, Vol 112, P 75-90

[62] H. Idriss, M. Scott, V. Subramani ''Introduction to hydrogen and its properties'' Compendium of Hydrogen Energy. http://dx.doi.org/10.1016/B978-1-78242-361-4.00001-7.

[63] A. Mohammadi, M. Mehrpooya ''A comprehensive review on coupling different types of electrolyzer to renewable energy sources'' Energy, 2018, Vol 158, P 632-655.

[64] N. F. Maged, N. M. Eskander, A. M Sharaf ''A Stand Alone Robust PV-FC-Eletrolyzer Utilization Scheme'' International Journal of Engineering Research, 2015, Vol 4, P 145-150

[65] K. Mazloomi, C. Gomes '' Hydrogen as an energy carrier: Prospects and challenges'' Renewable and Sustainable Energy Reviews, 2012, Vol 16, P 3024-3033

[66] E. I. Zoulias, N. Lymberopoulos ''Techno-economic analysis of the integration of hydrogen energy technologies in renewable energy-based stand-alone power systems'' Renewable Energy, 2007, Vol 32, P 680-696

[67] M. Z. Ibrahim, R. Zailan, M. Ismail, A. M. Muzathik ''Pre-Feasibility Study of Hybrid Hydrogen Based Energy Systems for Coastal Residential Applications'' Energy Research Journal, 2010, Vol 1, P 12-21.