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Research Article

Feasibility Study of PV-Wind-Fuel Cell Hybrid Power System for Electrification of a Rural Village in Ethiopia

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As the energy consumption is increasing in an alarming rate and peoples and international communities are well aware of environmental protection, alternative (i.e., renewable and fuel cell based) distributed generation (DG) systems have attracted increased interest. Wind-based and photovoltaic- (PV-) based power generation are two of the most promising renewable energy technologies. Fuel cell (FC) systems also show great potential in DG applications due to their fast technological development and the merits they have, such as high efficiency, zero or low emissions (of pollutant gases), and flexible modular structure. In this work, the techno-economic feasibility study (using HOMER) of emission-free hybrid power system of solar, wind, and fuel cell power source unit for a given rural village in Ethiopia called Nifasso (latitude of 9°58′40″N and longitude of 39°50′3″E with an estimated population of 1059) that can meet the electricity demand in a sustainable manner has been studied. The main power for the hybrid system comes from the solar and wind energy while the fuel cell and rechargeable batteries are used as a secondary and primary energy back up units, respectively. We can say storage as primary and secondary based on the sequence of operation. Hence, when there is shortage, first the battery discharges to fulfill the load demand and if the battery reaches to its allowable minimum capacity, it will stop further discharging and the fuel cell will operate so as to convert the stored hydrogen into electricity. In the result, different feasible alternative solutions have been obtained with a narrow range of COE which are better than the previously studied PV-wind-Genset hybrid set ups.

1. Introduction

Most people in the rural villages use kerosene for lamp, diesel for water pumping and flour mills, fire wood for cooking, and dry cells for radio and tape recorders. Desertification of the land is getting worse and worse due to deforestation and backward agricultural practices. Hence, the communities that live in the rural villages are suffering from lack of electricity. Therefore, women are forced to do their day-to-day domestic activities such as cooking, using fuel wood which leads to a rapid growth of deforestation; they travel long distances to fetch water; and they also use kerosene lamp at night. Additionally, due to lack of access to electricity, the communities in the rural villages are not able to benefit from social services such as clinics and schools sufficiently.

Therefore, village electrification is a vital step for improving the socioeconomic conditions of rural areas and crucial for the country's overall development. The villages' welfare is one of the main aims of the rural electrification program. Enormous benefits can be achieved in irrigation, food preservation, crop processing, agriculture, and rural small-scale industries [1, 2]. It creates employment opportunities for the villages' youth and promotes a better standard of life. Hence, availability of electricity reduces poverty and helps economic development by enhancing the health, education, and water supply (for drinking and irrigation) needs of the rural population [3–5].

Keeping in mind the above facts, the authors of this work believes that designing and implementing cost-effective renewable energy-based hybrid systems to supply electric loads is a best candidate solution.

Most feasibility studies in Ethiopia which have been conducted till now on the hybrid systems are PV/wind/Genset and PV/wind/hydro types. Hence, this work tries to look the other possibilities by incorporating fuel cell systems as secondary back-up units. But, several authors have studied the wind/PV/fuel cell, PV/fuel cell, and wind/fuel cell hybrid systems for different case studies in the world. For instance, Debnath et al. in [6] describe a hybrid power generation system suitable for remote area for agricultural application. The hybrid system is studied using HOMER software. The load has a peak value of 13 kW with a 2.2% day-to-day and hour-to-hour variation. To satisfy this load demand, a hybrid PV/FC/battery/electrolyzer system with 80 kW PV and 10 kW FC has been suggested with a COE of 0.431$/kWh [6].

2. Brief Note on HOMER

Hybrid Optimization Model for Electric Renewables (HOMER) software helps to find the least cost combination of components that meet a required load, based on an hourly analysis of the input variables, such as wind and solar data. For systems that meet the yearly load, the life-cycle cost is also estimated by the software. HOMER can be applied to a number of system designs: grid-connected or off-grid, stand-alone or distributed generation, and conventional or renewable technologies. The renewable technologies can be classified into three groups as power sources, storage, and loads [7].

In the category of power sources, the most common types are the following: photovoltaic (PV); wind turbine; hydropower; generators with different prime movers such as diesel, biogas, or coal-fired; electric utility grid; and microturbine or fuel cell. In the storage class, bank of batteries and hydrogen can be mentioned. With regard to loads, there are two types: primary and deferrable loads. The primary load is the electrical load that must be met at a specified time (e.g., lighting), and the deferrable load is the load that need not be met within a specified time but should be met within a certain time period (e.g., water pumping) [7].

The software is sufficiently intelligent to identify the proper timings of energy supplied to the components which are connected to the system. For systems which include batteries and a generator, the software can decide the times at which the batteries should be charged and when the generator should be operated. It also gives the deferrable load a lower priority than the primary load but a higher priority than charging the batteries. For this, there are two dispatch strategies that HOMER follows. A dispatch strategy is a set of rules by which the operation of the generator and the batteries is controlled whenever there is a shortage of energy from the renewable resources. There are two types of dispatch strategy: load following and cycle charging. The load following strategy enables HOMER to serve the deferrable load under two conditions. These are (a) when the storage tank is empty and (b) when the system produces excess electricity. Under a cycle charging strategy, the generator serves the deferrable load when it is able to produce more electricity than that needed by the primary load. If the storage tank is empty, then the deferrable load is considered a primary load and all the power sources serve the deferrable load as much as possible [7].

The software also provides a feature for carrying out sensitivity analysis, which enables the evaluation of the economic and technical feasibility of several technological options. This feature can also be used when there is doubt over the exact value of a certain input, such as the annual average wind speed, annual average solar radiation, diesel price, or the price of PV cells. Furthermore, when the data represent a range of applications, this feature can be used. The sensitivity analysis performs energy balance calculations on hourly basis for a whole year (8,760 hours). It compares the electric load for each hour to the energy that the system can supply during that hour. While carrying out the sensitivity analysis, the optimization process is repeated for each input value in the range so that the effect that changes in the value have on the results can be examined [7].

Nonetheless, this is not as simple as it may seem; as the number of sensitivity variables increases, the computational time of the software also increases, which could be considered a limitation or a challenge to using the software. When using the sensitivity analysis feature of the software, several sizes of each component must be considered in order to meet the load and the computation time is dependent on how many of them are used. To minimize the computation time, an iterative process needs to be followed. This is done by first considering just a small number of sizes and/or variables over a relatively large range to decrease the initial running time. After each successive run, a greater number of options and variables are added within the range in order to increase the resolution. Indeed, this takes quite a long time and can be considered as a limitation of the software [7].

Furthermore, similar to the several sensitivity variables that can be input into the sensitivity table, there is another search space table to which can be applied different sizes and quantities of the different system components, such as the size of PV array, generator, inverter, and the quantities of batteries and wind turbines. Again, this further lengthens the computation time of the software, as the software tries each and every component size and quantity. As in the previous case, the simulation can first be run coarsely, by minimizing the number of variables within the range. The results are then refined by adding a greater number of variables within the range. It should also be noted that the greater the number of variables within a certain range supplied to HOMER, the better the result. However, attention needs to be paid to the computation time [7].

After running the simulation, the results are given as a list of feasible system configurations, sorted by life-cycle cost. From the results, the least-cost systems, which are displayed in the first few rows of the list, can be chosen for implementation. The designer can also scan for other feasible systems in the list and decide to take any particular setup by evaluating the pros and cons of the setup against cost, renewable resource contribution, future price trend of the components, and so on. Following on from this, the technology options, component costs, and available resources were input to the software. HOMER used the inputs to provide different feasible system configurations, which were sorted according to their net present cost [7].

3. Load Estimation

Deciding on the load is one of the most important steps in the design of a hybrid system [8–10]. Primary load, which must be met immediately, and deferrable load, which must be met within a certain time, are both considered in this work. Electric load in the rural villages of Ethiopia can be assumed to be composed of lighting; radio and television, water pumps, health post, and primary schools load [7, 11]. The work indicated in [12] considered only lighting, radio, and television as community loads. Another study in Ethiopia [13] assumes additional electricity demand for cooking and for flour mills to the load together with the load considered in [7]. In this paper, barbers, shops, and church loads are incorporated additionally.

The daily power demand and energy need for the community of 289 households are estimated by considering basic domestic appliances such as television (70 W), CFLs of 11 W and 15 W for lighting, radio/tape (5 W), VCD/DVD player (15 W), refrigerator (70 W), "electric mitad" (2.5 kW), cell phone (2.5 W), and stove (1.5 kW).

The primary school consists of 8 classrooms, a director office, teacher's staff room, toilets, and a guard house. Each classroom is assumed to be installed with four 15 W CFLs (compact fluorescent lamps); one 15 W CFL is suggested for the teacher's staff room; one 15 W CFL is assumed for the director office; two 11 W CFLs are allowed for the toilet; one 11 W CFL for the guard house, and additional 4 CFLs (of 15 W) for external lighting are also considered. Evening classes are conducted from 18:00 to 21:00. Additionally, four computers (LCD desktop type of 200 W), one in the director office and three in the teacher's staff room; one printer (360 W); one photocopy machine (1000 W); tape/radio (5 W); one GSM wireless telephone (2 W); and two ceiling fan (80 W, each one in the director office and one in the teacher's staff room) are proposed.

For the health centers, having 3 rooms, 15 W CFL per room, one 15 W CFL for external lighting, one 11 W for the toilet, and one 11 W CFL for guard house are considered. When we come to the appliances used, it is based on the typical category I rural health clinic presented in [14]. Accordingly, basic small health post clinical equipment's such as vaccine refrigerator (134 W), a 15 W capacity microscope, a 135 W capacity centrifuge, a 2 kW water heater, a 400 W incubator, a 75 W television, a GSM wireless telephone (2 W), and three ceiling fans (each of 80 W in each room) are suggested.

For the community, two flour milling machines of 12.5 kW capacity each working from 9:00 to 12:00 and 14:00 to 18:00 with four 15 W CFLs for internal lighting (from 18:00 to 20:00) and two 15 W CFLs for external lighting (from 18:00 to 6:00) are assumed.

For the church, six 15 W CFLs in the internal lighting, one 15 W CFL in the "Bethlehem," one 15 W CFL in the office, four 11 W CFLs in the "meeting hall," four 15 W CFLs for the external lighting, and one 11 W for the guard house are assumed. Besides these, a GSM wireless telephone of 2 W is proposed.

There are a total of three shops assumed, and each shop is expected to have a radio/tape of 5 W and 15 W CFL. The CFLs are supposed to operate from 18:00 to 21:00.

In the community, two barbers are considered each having two hair clipping machines of 12 W. Additionally, one 15 W CFL for lighting between 18:00 and 21:00 is suggested for each.

The total primary load in weekend is expected to be less than weekdays. Because, some loads such as milling machines, school loads, and clinics will not operate. Hence, by considering some load reduction in weekends, the 24-hour load trend curve indicated in Figure 1 was obtained.

Water pumping system is required for households, schools, and health care centers. A minimum of 100 liters of water per day per family and 2400 liters/day for each pair of one health center and one primary school is suggested [7, 13]. Therefore, to accomplish this, we need to have three 1.528 kW of 40.416 l/m capacity (a total need of 4.584 kW) water pumps so as to pump water for the community which operates for four hours with the energy demand of 18.336 kWh. Again, we need to have one 1.119 kW of 20 l/m capacity water pump for the school and clinic that operates for two hours with the energy demand of 2.238 kWh. Hence, the total peak deferrable load is 5.703 kW, which needs 20.574 kWh energy.

A water storage capacity of 4 days is suggested requiring a storage capacity of 73.344 kWh for the community and 8.952 kWh for primary school and health centers. Hence, the total storage capacity is equal to 82.296 kWh. The storage capacities can be obtained by multiplying number of days with energy demand of each water pump [15, 16].

Up to 30% deferrable load reduction can be expected in the rainy season [7, 12, 17]. 15% load decrease for June, January, and September while 30% for July and August are assumed [13, 15]. There are no classes in July and August (annual break) and in January (semester break). With these assumptions, the monthly power consumption and energy demand of the water pumps are indicated in Figure 2.

4. HOMER Model of the Hybrid System

In this work, a hybrid system based on hydrogen technology is considered which needs a hydrogen producing unit (electrolyzer), a hydrogen storing unit (storage tanks), and a hydrogen utilizing unit (PEM fuel cell). However, the system is based on intermittent energy sources and is likely to experience large minutely, hourly, and daily fluctuations in energy input. Thus, it should be emphasized that the main purpose of the hydrogen storage system is to store energy over a long period of time (hour to hour and season to season). Other small short-term energy storage such as a battery must also be included to supply power during transient load conditions. Figure 3 shows the model and the hybrid setup in HOMER.

4.1. Resource Inputs. The monthly average wind speed for the study area obtained from [18] and National

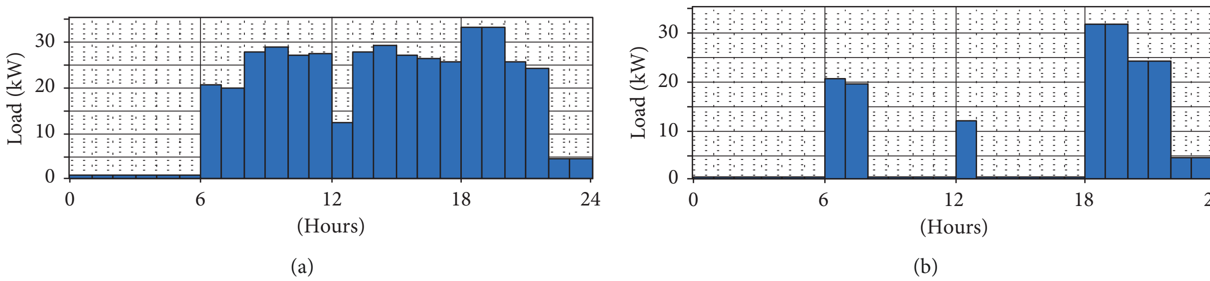


Figure 1: Primary load daily profiles: (a) weekday; (b) weekend.

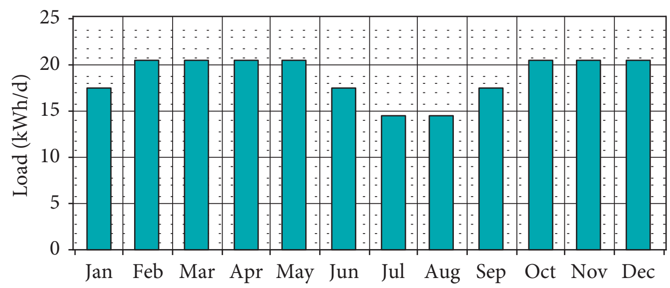


Figure 2: Monthly deferrable load profiles.

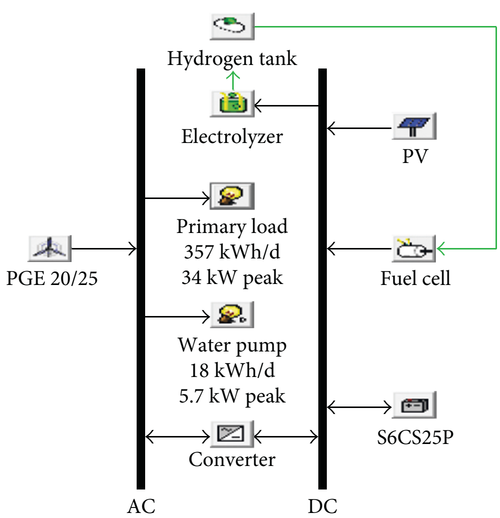


Figure 3: HOMER model of the hybrid power system.

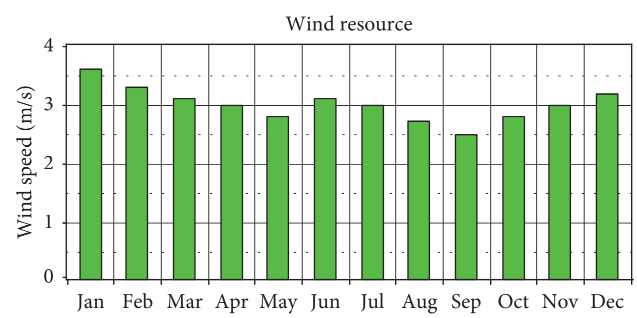


Figure 4: Monthly average wind speeds at 10 m.

Meteorological Service of Ethiopia were fed into HOMER. Figure 4 shows the average wind resource profile of each month at 10 m above the surface of the earth.

The probability density function of the wind speed synthesized by HOMER is also given in Figure 5. The software estimates a Weibull $k = 1.87$ and $c = 3.39$ m/s.

In a similar way, the solar energy potential for the study area was fed into HOMER, and this is shown in Figure 6. This figure also shows the clearness index which HOMER generates for the analysis. The clearness index is the fraction of solar radiation transmitted through the atmosphere which strikes the surface of the earth, and hence, it is a measure of the clearness of the atmosphere. It is a dimensionless number between 0 and 1, defined as the surface radiation divided by the extraterrestrial radiation [7, 16, 19].

Many literatures reported that typical values for the monthly average clearness index range from 0.25 (a very cloudy month) to 0.75 (a very sunny month) [7, 20]. And this fact can be seen clearly in Figure 6. Note also that, in Figure 6, clearness index falls in between 0.4 and 0.8, which is the indication of the availability of a relatively strong solar potential in the study area.

The monthly temperature variation which is fed into the HOMER software is indicated in Figure 7. HOMER uses the ambient temperature to calculate the PV cell temperature and to consider temperature effect in the PV system.

4.2. Summary of Additional Inputs for Simulation. The capital, replacement, and operational and maintenance cost of each component in the hybrid system are given in Table 1. The table also contains the components' average operational life year and the size and/or quantities considered in the

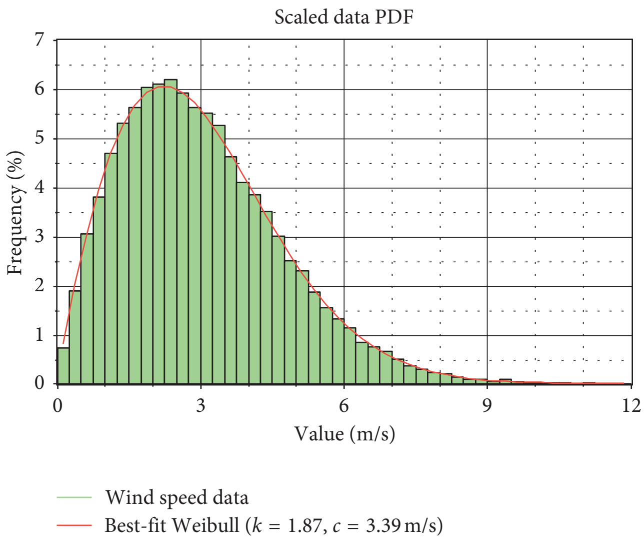


FIGURE 5: Wind speed probability density function at 10 m.

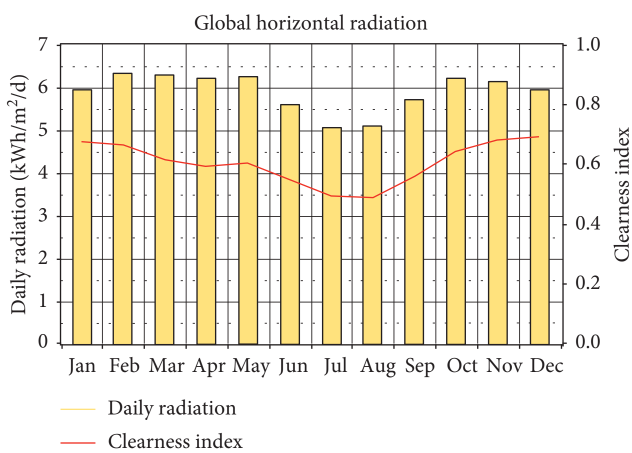


FIGURE 6: Monthly average radiations.

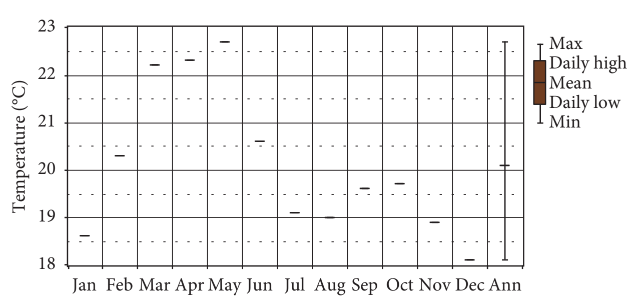


FIGURE 7: Monthly average ambient temperatures.

study. Therefore, as the software searches the optimum system combination, it uses the input values summarized in the table. Besides this input values, sensitivity variables are also defined for PV and FC costs.

5. Simulation Results and Discussions

5.1. Optimization Results. Figure 8 shows some optimization results (which are part of the numerous alternative solutions from rank 1 up to 26) that are the possible configurations able to feed the system total load. Despite the numerous alternatives with equal renewable fraction, the choice of optimal system type is restricted by the varying nature of initial capital, net present cost, excess electricity, and COE of each set up. Accordingly, the one which is marked in blue color (the fifth rank) in which fuel cell operates for 2,731 hours/year is the best optimum PV-wind-fuel cell hybrid system configuration. Because, from rank 1 up to rank 4, the system configurations are PV only and PV-fuel cell types with small changes in COE and NPC from the selected one. Moreover, in the fifth rank, due to the availability of all power sources (PV, wind, and fuel cell), the reliability of the hybrid system will also be improved with only small addition of cost.

A hybrid power system containing PV, wind, and fuel cell power sources marked in blue color in Figure 8 can be summarized by Table 2.

As it can be seen clearly in the fifth rank that is marked in blue in Figure 8, the capacity shortage is reported as 0.01 which is nearly zero. Furthermore, the system report shows that there is an excess electricity of 43,460 kWh/yr (18.9%). This excess electricity is not discouraging as it can be used to serve the load growth that might come in near future. Besides this, this excess electricity can be utilized as a compensation for the losses in the distribution network.

Figure 9 shows the detailed net present cost share by each component of the optimal hybrid set-up supported by a bar graph. Hence, the net present cost share of each component in decreasing order can be recognized as PV, battery, wind turbine, converter, electrolyzer, hydrogen tank, and fuel cell.

Figure 10 displays the monthly average electricity production by each power unit. Hence, as it can be seen clearly, most of the electricity production is being shared by the PV followed by the wind turbine. But, the power production share by the fuel cell, even though it is significant, is small as compared with the PV and wind turbine power unit outputs. This is also presented in Table 3.

The monthly average hydrogen production by the electrolyzer is given in Figure 11. Recall that an electrolyzer converts the excess electricity into hydrogen by the electrolysis of water. As the simulation result reports that the total hydrogen production and total hydrogen consumption were found to be 684 kg/yr and 670 kg/yr, respectively. Besides this, the hydrogen tank autonomy (expressed in hours) which is defined as the ratio of the energy capacity of the hydrogen tank to the electric load was reported as 32.

5.2. Sensitivity Analysis Result. Figure 12 shows sensitivity of the optimal system type under the imposed price variation of sensitive components. The PV capital cost multiplier on the Y axis and FC capital cost multiplier on the X axis are considered as sensitivity variables. In the graph, the total net present costs (NPCs) of the most cost-effective systems are also displayed.

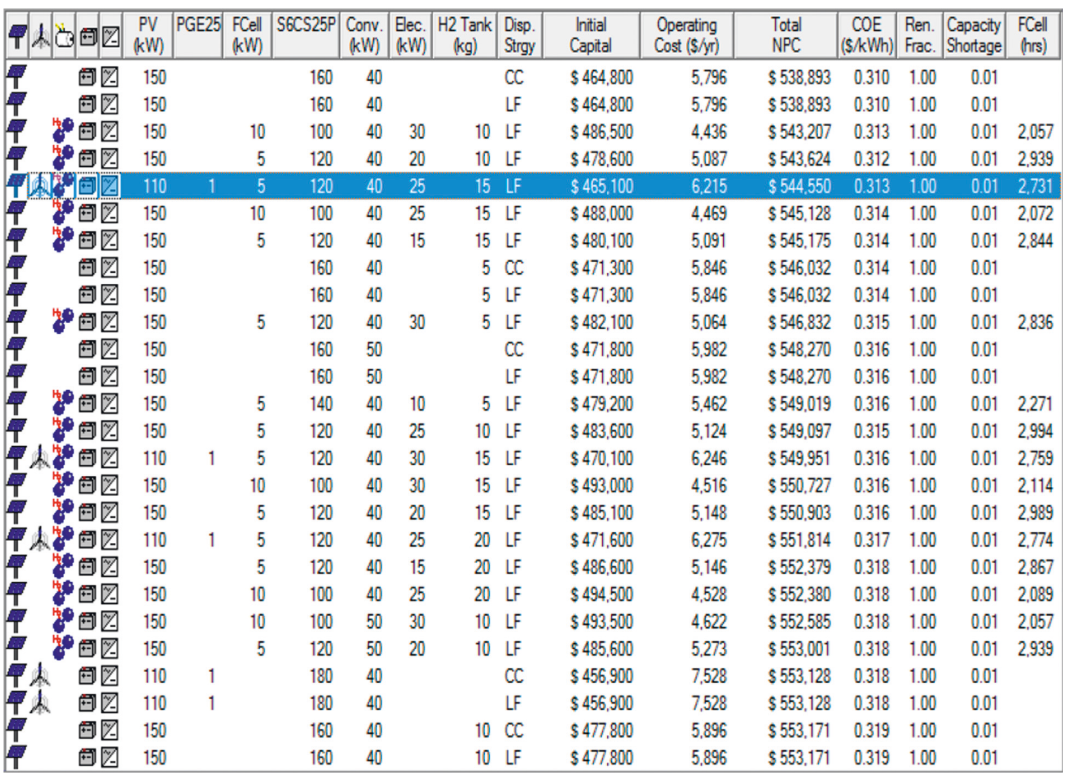
6. Conclusions

In short, this work addressed a techno-economic analysis of PV/wind/FC hybrid power system preceded by community load estimation and resource collection.

Table 1: Summary of additional inputs for HOMER simulation.

	PV array	Wind turbine (PGE20/25)	Fuel cell	Electrolyzer	Converter	Battery (Surrette 6CS25P)	Hydrogen tank
Unit	kW	kW	kW	kW	kW	Ah	kg
Size	1	25	1	1	1	1156	1
Capital cost ($)	2,000	55,000	3,000	1,000	700	855	1,300
Replacement cost ($)	2,000	36,667	2,000	667	700	555	867
O&M cost ($/yr)*	0 (0%)	1,100 (2.5%)	$0.02/hr	5 (0.5%)	0 (0%)	8.55 (1%)	13 (1%)
Size considered	0, 50, 80 100, 110, 150, 200	—	0, 5, 10, 15, 20, 25	0, 5,10, 15, 20, 25, 30, 50, 100	0, 30, 40, 50	—	0, 5, 10, 15, 20, 25, 30, 50
Quantities considered	—	0, 1, 2, 3	—	—	—	0,80, 100, 120, 140, 160, 180	—
Life time	25 yrs	25 yrs	40,000 hrs	25 yrs	15 yrs	9,645 kWh	25 yrs

*Considering O&M cost as 0–10% of the capital cost is a standard procedure.



PV (kW)	PGE25	FCell (kW)	S6CS25P	Conv. (kW)	Elec. (kW)	H2 Tank (kg)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	FCell (hrs)
150			160	40			CC	$ 464,800	5,796	$ 538,893	0.310	1.00	0.01	
150			160	40			LF	$ 464,800	5,796	$ 538,893	0.310	1.00	0.01	
150		10	100	40	30	10	LF	$ 486,500	4,436	$ 543,207	0.313	1.00	0.01	2,057
150		5	120	40	20	10	LF	$ 478,600	5,087	$ 543,624	0.312	1.00	0.01	2,939
110	1	5	120	40	25	15	LF	$ 465,100	6,215	$ 544,550	0.313	1.00	0.01	2,731
150		10	100	40	25	15	LF	$ 488,000	4,469	$ 545,128	0.314	1.00	0.01	2,072
150		5	120	40	15	15	LF	$ 480,100	5,091	$ 545,175	0.314	1.00	0.01	2,844
150			160	40		5	CC	$ 471,300	5,846	$ 546,032	0.314	1.00	0.01	
150			160	40		5	LF	$ 471,300	5,846	$ 546,032	0.314	1.00	0.01	
150		5	120	40	30	5	LF	$ 482,100	5,064	$ 546,832	0.315	1.00	0.01	2,836
150			160	50			CC	$ 471,800	5,982	$ 548,270	0.316	1.00	0.01	
150			160	50			LF	$ 471,800	5,982	$ 548,270	0.316	1.00	0.01	
150		5	140	40	10	5	LF	$ 479,200	5,462	$ 549,019	0.316	1.00	0.01	2,271
150		5	120	40	25	10	LF	$ 483,600	5,124	$ 549,097	0.315	1.00	0.01	2,994
110	1	5	120	40	30	15	LF	$ 470,100	6,246	$ 549,951	0.316	1.00	0.01	2,759
150		10	100	40	30	15	LF	$ 493,000	4,516	$ 550,727	0.316	1.00	0.01	2,114
150		5	120	40	20	15	LF	$ 485,100	5,148	$ 550,903	0.316	1.00	0.01	2,989
110	1	5	120	40	25	20	LF	$ 471,600	6,275	$ 551,814	0.317	1.00	0.01	2,774
150		5	120	40	15	20	LF	$ 486,600	5,146	$ 552,379	0.318	1.00	0.01	2,867
150		10	100	40	25	20	LF	$ 494,500	4,528	$ 552,380	0.318	1.00	0.01	2,089
150		10	100	50	30	10	LF	$ 493,500	4,622	$ 552,585	0.318	1.00	0.01	2,057
150		5	120	50	20	10	LF	$ 485,600	5,273	$ 553,001	0.318	1.00	0.01	2,939
110	1		180	40			CC	$ 456,900	7,528	$ 553,128	0.318	1.00	0.01	
110	1		180	40			LF	$ 456,900	7,528	$ 553,128	0.318	1.00	0.01	
150			160	40		10	CC	$ 477,800	5,896	$ 553,171	0.319	1.00	0.01	
150			160	40		10	LF	$ 477,800	5,896	$ 553,171	0.319	1.00	0.01	

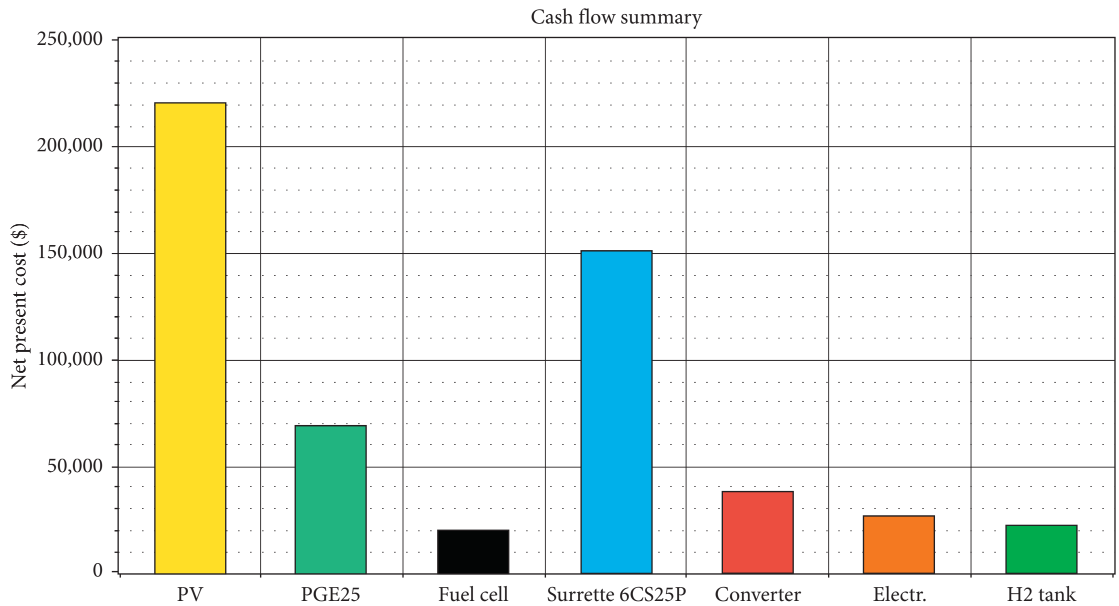
Figure 8: Some of the optimization results.

Table 2: System architecture and cost summary.

System architecture		Cost summary	
110 kW PV array	120 × Surrette 6CS25P	Total NPC	$544,550
1 × PGE 20/25	25 kW electrolyzer	Initial capital	$465,100
5 kW fuel cell	15 kg hydrogen tank	Operating cost	$6,215/yr.
40 kW converter	LF dispatch strategy	Levelized COE	$0.313/kWh

Regarding the potential of the resources, it is observed that, the wind energy potential of the site is of class 1 type according to the US Department of Energy (DOE) wind mapping. Such wind energy potential, although it may not be sufficient for a large independent wind farm, is a viable preference if incorporated into other energy conversion systems such as PV and others [7]. The data sources for solar energy also confirmed the availability of huge potential of solar energy at the site.

The result of techno-economic feasibility study shows that there are numerous alternative feasible hybrid set ups with 100% contribution by the renewable resources and narrow range of COE (0.310$/kWh to 0.328$/kWh). Accordingly, the community electric demand can be satisfied by a hybrid system power source containing 110 kW PV, one PGE 20/25 wind turbine, a 40 kW converter, 120 Surrette



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	220,000	0	0	0	0	220,000
PGE 20/25	55,000	0	14,062	0	0	69,062
Fuel cell	15,000	4,259	349	0	−683	18,926
Surrette 6CS25P	102,000	49,547	13,116	0	−14,225	151,038
Converter	28,000	11,683	0	0	−2,175	37,509
Electrolyzer	25,000	0	1,598	0	0	26,598
Hydrogen tank	19,000	0	1,918	0	0	21,418
System	465,100	65,490	31,042	0	−17,082	544,550

FIGURE 9: Cost share by each component.

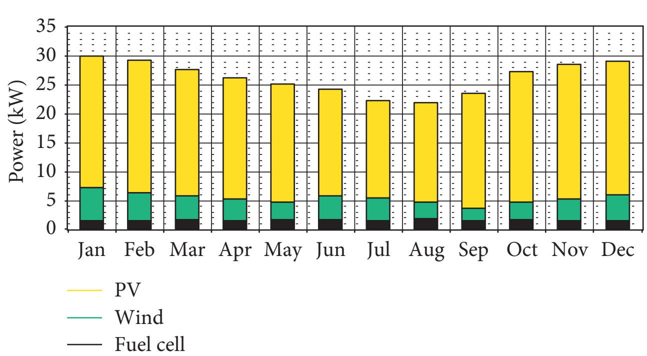


FIGURE 10: Monthly average electricity productions by the optimal hybrid PV-wind-FC power units.

TABLE 3: Electric power production and consumption.

Production			Consumption		
Power unit	kWh/yr	%	Load type	kWh/yr	%
PV array	183,017	80	AC load	129,291	79
Wind turbine	33,461	14	Deferrable load	6,703	4
Fuel cell	13,395	6	Electrolyzer	27,511	17
Total	229,874	100	Total	163,505	100

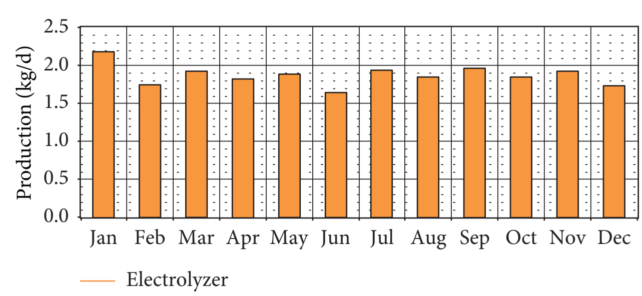


FIGURE 11: Monthly average hydrogen productions by the electrolyzer.

S6CS25P batteries, a 5 kW fuel cell, a 25 kW electrolyzer, and a 15 kg hydrogen tank. This hybrid system needs $465,100 initial capital, $6,215 for operation and maintenance, and $544,550 total NPC over the 25 life-year horizon. With these economics, the COE of the selected hybrid system was found to be 0.313$/kWh.

Neglecting other factors, in terms of COE, the result obtained in this study is comparable and even may be better than what previously studied PV-wind-Genset hybrid set up showed. For instance, in [7, 13], the range of COEs reported are 0.322$/kWh to 0.518$/kWh and 0.302$/kWh to 0.392$/kWh, respectively. But, the renewable fraction in both researches is poor—being too less than unity. Moreover, due to Genset package, there is a considerably high level of emission to the atmosphere such as CO_2, CO, unburned HC,

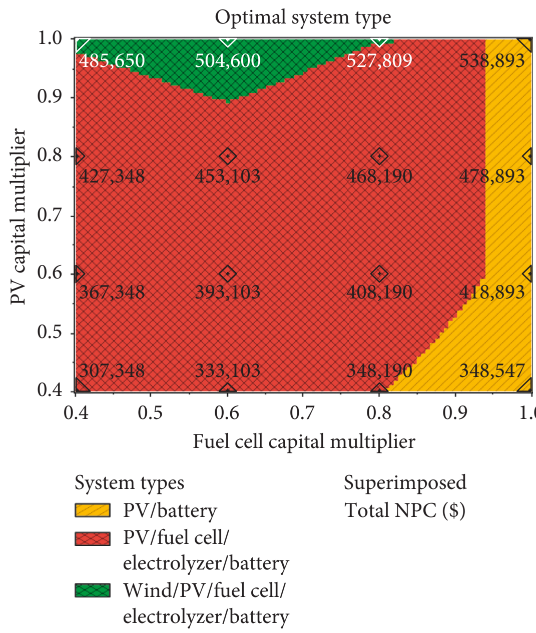


Figure 12: Sensitivity of the optimal system type for PV and FC capital multiplier variations.

SO_2, NO_X, and particulate matter (smoke, soot, and liquid droplets) emitted per unit fuel consumed by the generator. Hence, a hybrid PV-wind-fuel cell power system can be considered as a good choice in this regard.

Data Availability

The wind speed and solar radiation data used in this study were obtained from NASA website and National Meteorological Service of Ethiopia. The cost data for each hybrid system component can be found in IRENA (International Renewable Energy Agency) cost release report. These data can also be obtained from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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References

[1] S. Touati, A. Belkaid, R. Benabid, K. Halbaoui, and M. Chelali, “Pre-feasibility design and simulation of hybrid PV/fuel cell energy system for application to desalination plants loads,” *Procedia Engineering*, vol. 33, pp. 366–376, 2012.

[2] S. Kumar Kotte, Y. Ravisankar, A. Ahad, and S. Babu, “Dynamic modeling and simulation of a wind fuel cell hybrid energy system for standalone systems with hybrid optimization model for electrical renewable,” in *Proceedings of International Colloquiums on Computer Electronics Electrical Mechanical and Civil*, Mulavoor, Kerala, 2011.

[3] P. Ozaveshe and T. C. Jen, “The energy cost analysis of hybrid systems and diesel generators in powering selected base transceiver station locations in Nigeria,” *Energies*, vol. 11, no. 3, p. 687, 2018.

[4] O. H. Mohammed, Y. Amirat, M. Benbouzid, and A. A. Elbaset, “Optimal design of a PV/fuel cell hybrid power system for the city of Brest in France,” in *Proceedings of 2014 First International Conference on Green Energy (IEEE ICGE 2014)*, pp. 119–123, Sfax, Tunisia, March 2014.

[5] K. Mohamed and M. El Ganaoui, “Feasibility study for the production of electricity using a hybrid PV-wind-generator system in a remote area in Comoros,” *International Journal of Research and Reviews in Applied Sciences*, vol. 33, no. 2, 2017.

[6] D. Debnath, A. C. Kumar, and S. Ray, “Optimization and modeling of PV/FC/battery hybrid power plant for standalone application,” *International Journal of Engineering Research and Technology*, vol. 1, no. 3, 2012, ISSN: 2278-0181.

[7] G. Bekele, *The study into the potential and feasibility of standalone solar-wind hybrid electric energy supply system for application in Ethiopia*, Ph.D. thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 2009.

[8] M. H. Kebede, “Design of standalone PV system for a typical modern average home in Shewa Robit Town-Ethiopia,” *American Journal of Electrical and Electronic Engineering*, vol. 6, no. 2, pp. 72–76, 2018.

[9] K. Gupta, A. Gupta, I. Aziz, A. Sharma, U. Ul Khaliq, and S. Kumar, “Feasibility of solar wind hybrid renewable energy in India,” *International Journal of Engineering Research and General Science*, vol. 5, no. 2, 2017, ISSN 2091-2730.

[10] H. Chaouali, H. Othmani, M. Selméne, D. Mezghani, and A. Mami, “Energy management strategy of a PV/fuel cell/ supercapacitor hybrid source feeding an off-grid pumping station,” *International Journal of Advanced Computer Science and Applications*, vol. 8, no. 8, 2017.

[11] G. Bekele and G. Boneya, “Design of a photovoltaic-wind hybrid power generation system for Ethiopian remote area,” *Energy Procedia*, vol. 14, pp. 1760–1765, 2011.

[12] B. Tamrat, “*Comparative analysis of feasibility of solar PV, wind and micro hydropower generation for rural electrification in the selected sites of Ethiopia*,” M.Sc. thesis, Addis Ababa Institute of Technology, Addis Ababa, Ethiopia, 2007.

[13] G. Tadesse, “*Feasibility study of small hydro/PV/wind hybrid system for off-grid rural electrification in Ethiopia*,” M.Sc. thesis, Addis Ababa Institute of Technology, Addis Ababa, Ethiopia, 2011.

[14] USAID, *Powering Health: Electrification Options for Rural Health Centers*, United States Agency for International Development, Washington, DC, USA, 2005.

[15] M. H. Kebede and G. B. Beyene, “*Dynamic modeling and techno-economic analysis of PV-wind-fuel cell hybrid power system: the case study of Nifasso*,” M.Sc. thesis, Addis Ababa Institute of Technology, Addis Ababa, Ethiopia, 2014.

[16] V. Dash and P. Bajpai, “Power management control strategy for a stand-alone solar photovoltaic-fuel cell battery hybrid system,” *Sustainable Energy Technologies and Assessments*, vol. 9, pp. 68–80, 2015.

[17] M. H. Kebede, P. Mukilan, and G. B. Beyene, “Dynamic modeling and optimization of self-sustaining solar-wind hybrid street lighting system: the case study of Addis Ababa city,” *Journal of Advanced Research in Dynamical and Control Systems*, vol. 9, no. 17, 2017.

[18] NASA, 2012, http://eosweb.larc.nasa.gov/cgibin/sse/retscreen.cgi?email=rets%40nrcan.gc.ca&step=1&lat=9.9777892&lon=39.8342339&submit=Submit.

[19] C. Lodha and V. Shukla, "Power management of a stand-alone photovoltaic/fuel cell hybrid energy system," *International Journal of Scientific Research Engineering and Technology*, vol. 5, no. 4, 2016.

[20] V. Vijaya Kumar Naik, G. Jaya Krishna, and N. Visali, "Review of optimal integrated control strategies for renewable energy based micro grid system," *International Journal of Pure and Applied Mathematics*, vol. 118, no. 15, pp. 17–26, 2018.