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Development of Stand-Alone Green Hybrid System for Rural Areas

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Abstract: Despite the tremendous efforts exhibited by various utilities around the world during the past few years, there are still exceedingly many remote regions unreached by the electrical grid. For those regions, the enormous available potential of renewable energy resources is believed to be useful for the development of a stand-alone power supply system. This paper presents the modeling of a stand-alone hybrid system for the remote area of Ethiopia. A comparison of the economic performance of various scenarios of a stand-alone photovoltaic (PV)-wind hybrid system, with battery storage and diesel as a backup for electrifying remote rural areas, is presented. Therefore, a practical example, Kutur village of Awlio kebele of the Axum district, Ethiopia (which is 30 km away from the closest national grid) is considered for this research. Two electric load scenarios are estimated by considering the set of incandescent and efficient lamps for lighting for the 120 existing households. The above-mentioned solar radiation and wind speed are then used as an input to simulate the hybrid set-up for the high and low load estimation using HOMER software. The simulation result shows that the net present costs (NPC) corresponding to the high and low load scenarios is $262,470 and $180,731, respectively. Besides, an essential load forecasting is performed to see the effect of the increase in electric demand of the community on the required investment to install a stand-alone hybrid set-up. The NPC after load forecasting is found to be more than three folds of the NPC required for the reference year. In both cases, the simulation results indicate that using a stand-alone PV-wind hybrid system with battery storage and a diesel generator as a backup for electrifying Kutur village is cost-effective and comparable against the cost required for electrifying the village by extending the grid.

Keywords: grid access; hybrid PV-wind; battery storage; diesel generator; HOMER

1. Introduction

Renewable energy generation sources are essential for providing green energy to remote rural areas. Development of green energy-based stand-alone systems is possible with the proper utilization of solar photovoltaic (PV) and wind energy sources. The electric supply system throughout the world is the interconnected system (ICS). Therefore, most of the remote rural areas that are located far off from the grid did not get electric access since the power to the grid is insufficient and it is not cost-effective to extend the medium voltage distribution system, even though the development cost within the country is cheap. Consequently, the rural areas have been dependent on local solutions for electricity supply. These areas have been using traditional biomass as a source of energy for baking as well as cooking and oil for lighting purpose. However, the current price increase in imported oil and the harmful effects of fossil fuels on the local and global environment motivate the search for other alternatives.

The Ethiopian interconnected system (ICS) consists of fourteen hydro, six diesel standbys, one geothermal, three wind farms and one biomass/waste power plants with the installed capacity of 3814.20 MW, 99.17 MW, 7.30 MW, 324 MW and 25 MW, respectively, which bring a total of 4269.67 MW [1]. Despite the abundance of potential resources suitable for the energy sector development, the level of electricity production can improve from the current capacity of 4269.67 MW. As a result, the overall access to electricity is increased to 35% from 13% [1]. The government also has a plan to exploit more energy from wind and geothermal sources to improve access to electricity by up to 50% in the coming five years. Ethiopian Electric Power (EEP), the sole electric power producer and supplier in the country, is therefore endowed to fulfil the plan by increasing the production up to 10,000 MW by including renewable energy resources and especially wind [2]. Moreover, there is also a program to give electric access from solar resources to more than 150,000 households of remote rural areas of the country with sufficient solar radiation resource in the coming five years [2].

Despite the availability of the generation, the rural areas of Ethiopia are facing the problem of no electricity access due to various financial and demographic limitations in the grid extension. However, these limitations can be minimized by looking for alternative energy resources, which can be used as stand-alone systems for providing electric access to remote communities. Therefore, solar and wind can be the first option, since these resources are available in those areas free of cost.

Related Work

Various studies performed on the hybrid systems in different rural areas of the world showed that the hybrid set-up is cost-effective and reasonable for electrifying rural areas. This was demonstrated using different approaches, such as analytical models including life cycle cost (LCC) and loss of power supply probability (LPSP). Additionally, researchers used various software's like MATLAB and HOMER to obtain the best-optimized result for the specific area in which the research work has been conducted. Salwan [3] proposed a hybrid system as a renewable resource of power generation for grid-connected applications in three cities in Iraq. The proposed system was simulated using MATLAB solver. Barley et al. [4] used hourly values of wind speed and solar radiation for one year for their models to capture seasonal effects, diurnal cycles, storm cycles and stochastic variations. For that purpose, a quasi-steady-state time-series model was utilized to determine approximate least-cost designs and a stochastic model for accurately determining the cost of energy (COE) and unmet load for each of the designs indicated by the simple model. Finally, actual resource data from the region were processed to indicate that the combination of wind and PV is more cost-effective than either component alone. Fieldler et al. [5] studied PV-wind hybrid systems for eleven locations in Sweden. They aimed for the evaluation of system cost, cost of energy, the effect of load size, and compared the cost of the hybrid system against the cost required by a PV system alone. The system was modeled to supply electricity for single-family houses. HOMER software was used for the sizing of the hybrid systems based on the net present costs (NPC). Mandal et al. [6] presented the model for optimal sizing of the stand-alone hybrid system to electrify remote areas of Bangladesh. Aberilla et al. [7] designed and assessed the environmental sustainability of a low-level stand-alone energy system to electrify rural communities in the Philippines. Zhao et al. [8] assessed the technical feasibility of off-grid PV-wind/adiabatic compressed air energy storage depended on the hybrid power system to electrify a remote mobile base station. Moner-Girona et al. [9] presented a case study related to the decentralization of the rural electrification in Kenya for speeding up the universal energy access program. Gabra et al. [10] compared the techno-economic analysis of off-grid wind microgrids with PV and diesel-based systems in Africa. Ariyo et al. [11] optimized the performance of an off-grid hybrid power system developed for the senate building, university of Ilorin, Nigeria. Yeshalem et al. [12] designed a stand-alone hybrid PV-wind power system for a remote mobile base station in Ethiopia. Jariso et al. [13] developed an off-grid PV energy system to supply electricity to a remote health center in south-west Ethiopia. Further, in [14], Jariso et al. optimized the performance of a hybrid system developed for a health center south-west Ethiopia. After the critical review of the mentioned works of literature, it is concluded that many of them have not utilized load forecasting to show the variation of the demand on the installation cost. On top of that, many did not compare the total cost of the extension of national grid; instead, compared the hybrid system with one of the components alone.

Henceforth, this research is conducted to show the impact of population growth on the demand of the site by using load forecasting as well as to compare the cost of the hybrid system against the cost required to extend the national grid. The following are the significant contributions of this research paper:

1. Modeling of a stand-alone hybrid PV-wind hybrid system, with battery storage and diesel as a backup for electrifying remote rural areas of Ethiopia;
2. Actual local metrological solar irradiation and wind speed data are considered to assess the energy outputs from the distributed generation sources;
3. A comparison of the economic performance of various scenarios of the stand-alone PV-wind hybrid system, with battery storage and diesel as a backup for electrifying remote rural areas is presented;
4. Basic load forecasting is performed to see the effect of the increase in electric demand of the community on the required investment to install a stand-alone hybrid set-up;
5. A comparative analysis of the cost of the hybrid system against the cost required to extend the national grid is performed so as to provide the best economic signals.

The rest of the manuscript is organized as follows. Section 2 provides detailed information about the selected case study area. Section 3 discusses the methodology utilized to perform the research work. Section 4 presents the resource assessment and load estimation of the selected case study area. Section 5 discusses the modeling of the hybrid system and cost analysis of the grid extension. Section 6 presents the result and discussion followed by the conclusion.

2. Study Area

Kutur village of Awlio kebele (ward) of the Axum district is located 30 km away from the closest national grid. The village was selected due to the possibility of its grid extension, and hence the comparison of the installation cost of a stand-alone green system with an extended grid system could be performed. Axum district is located at the latitude of 14°07′N and longitude of 38°43′E and found to have 4.28 m/s wind speed at the height of 10 m, and 6.19 kWh/m^2/day solar radiation. Two electric load scenarios were estimated by considering the set of incandescent and efficient lamps for the lighting of 120 existing households.

Figure 1 shows the settlement of the people of Kutur village of Awlio Kebele found in Axum district and their traditional use of firewood for baking. As is shown in the figure, the area has a sewing workshop. In addition to this, it has small shops, which supply the daily requirements of the community. It also shows the traditional "mitad" or stove used for baking bread and "Injera". Firewood is the primary source of energy, and hence the forests found in the area are highly exposed to deforestation. Therefore, this work also shows the possibility of using a PV-wind hybrid system for electrifying the village and its significance in reducing deforestation caused by the people of the area.

Figure 1. Kutur Village.

3. Methodology

As was mentioned in the introduction, this research is mainly concerned with looking into the better options of energy sources to electrify villages in remote areas of Ethiopia that are off the existing national grid by comparing against the cost needed to extend the national grid. The main concern is the assessment of resource potential and the modeling of the stand-alone hybrid system by analyzing data taken from different authorities. The field data, which include the number of households and their daily activity related with energy consumption, were collected by visiting the selected village, and some pictures were taken, which show the settlement and the wood the residents use as the source of energy. However, wind speed and solar radiation data of the selected sites collected from National Aeronautics and Space Administration (NASA) were compared with data from the National Meteorology Service Agency (NMSA) of Ethiopia due to their better accuracy and understanding of the demographic conditions and incorporation of the local weather effects, if any. Moreover, the data needed for calculating the cost of extending the grid were taken from EEP, and were analyzed using an interlinked Microsoft office excel spreadsheet prepared by the universal energy access program (UEAP). Additionally, the exponential load forecasting method was used to consider the effect of change of electric load of the community within the lifespan of the project, which is 25 years. Finally, the hybrid system was modeled and simulated using HOMER software, based on the primary and secondary analyzed data so as to get the best optimization. Figure 2 presents a flow chart of the research progress.

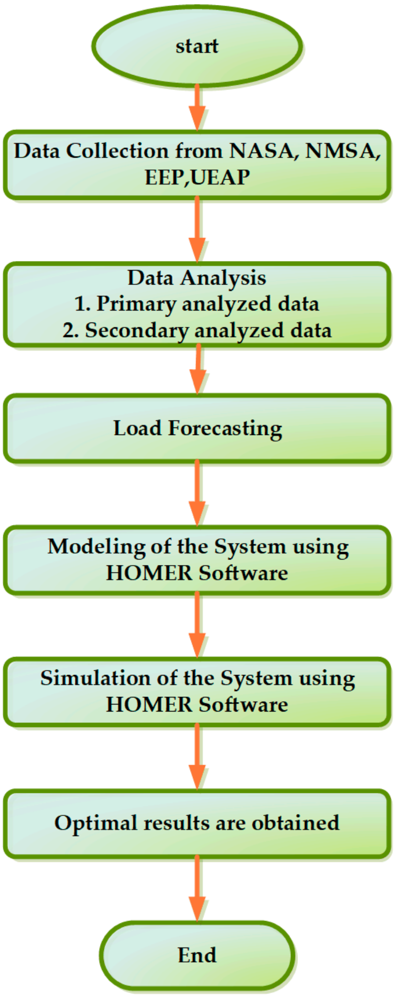

Figure 2. Flow chart of the research process.

4. Resource Assessment and Load Estimation

The solar data available from most of the towns of Ethiopia relate to sunshine duration, and the wind data are related to the wind speed measured at the height of 2 m. In order to assess the availability of solar radiation and wind speed resources in Axum district, data were taken from different sources, including the NMSA. The data obtained from NMSA were then compared against the data from NASA, to check for its accuracy and a better understanding of the demographic conditions. Further, local weather effects, if any, were incorporated.

4.1. Assessment of Solar Radiation

The assessment of the potential for the solar radiation of the selected area was done by taking data from different sources. These are NASA and NMSA of Ethiopia, as well as data assessed by [2] for the regions of the country. In the first approach, the data taken from the NMSA were analyzed using a mathematical approach based on the sunshine duration collected in the past six consecutive years. The sunshine duration data taken from the NMSA of Ethiopia, Mekelle branch, were converted into solar radiation using the Angstrom radiation–sunshine relation presented in [15].

The measurements were taken for six consecutive years. As can be seen in Table 1, the data for years 2010, 2012 and 2013 are full, but for 2009, 2011 and 2014 measurements were taken partially; hence, the three years with full data were taken to convert into solar radiation. Therefore, for calculating the radiation in kWh/m^2 from the sunshine duration using the Angstrom radiation–sunshine relation [15], the values for the regression coefficients α and β were taken to be 0.30 and 0.50, respectively. Finally, this result was compared with the data taken from NASA, and it was found that the annual average solar radiation obtained from NMSA (which is 6.21 kWh/m^2) is nearly equal to the value taken from NASA (which is 6.15 kWh/m^2). Consequently, 6.21 kWh/m^2 was then taken as an input to the solar resource in the modeling of the hybrid system. The monthly average solar radiation of Axum for the data taken from NMSA and NASA is shown in Tables 1 and 2, respectively.

Table 1. Solar radiation of Axum in kWh/m^2/day data from NMSA.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average in kWh/m^2/day
2010	6.11	6.39	7.22	6.94	7.22	6.11	5.28	5.56	6.39	6.67	6.11	5.83	
2012	6.11	6.11	6.94	7.5	7.5	6.11	4.72	5.56	6.67	6.67	5.83	5.83	
2013	5.83	6.39	6.67	6.67	6.67	5.83	5.28	4.44	5.83	6.67	6.11	5.83	
Monthly average	6.02	6.3	6.94	7.04	7.13	6.02	5.09	5.19	6.3	6.67	6.02	5.83	6.21

Table 2. Solar radiation of Axum in kWh/m^2/day data from NASA.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
22-year Average	5.76	6.2	6.59	6.92	6.74	6.49	5.8	5.58	6.25	6.23	5.88	5.51	6.15

From the results shown in Table 1 it can be seen that the solar radiation of the area is highest in May, reaching a value of 7.13 kWh/m^2/day, and is lowest in July (which has a value of 5.09 kWh/m^2/day). Hence, depending on the results obtained from NMSA and NASA, it can be concluded that the area has excellent potential for using the photovoltaic system for rural electrification.

Figure 3 presents the monthly distribution of solar radiation of Axum city according to the data obtained from NMSA.

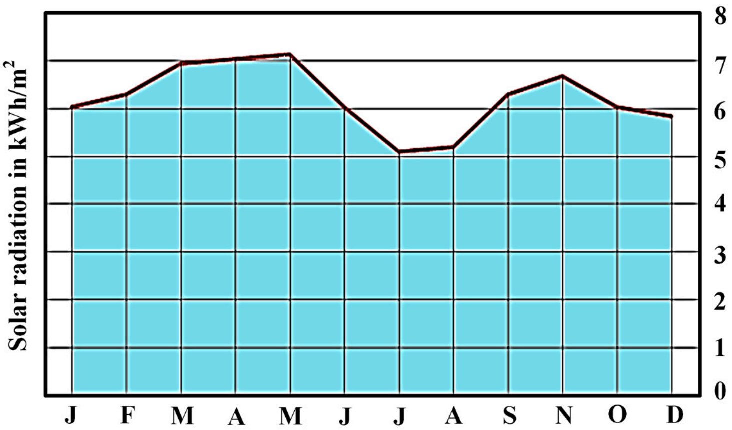

Figure 3. Solar radiation of Axum (data from NMSA).

4.2. *Assessment of Wind Potential*

To maintain the current economic growth of Ethiopia, it needs a 38-fold increase in its electric supply by 2030; hence, new sources of energy are urgently needed. Subsequently, the answer to this may lie in wind energy, since intense and reliable winds of the country can generate a substantial amount of electricity at a reasonable cost, which can even be exported to neighboring countries. The areas that can provide the highest potential for wind energy are the northern, central, eastern and southwestern part of the country [16]. Axum is also one of the districts found in the northern part of Ethiopia, which has good potential in wind and solar resources. However, to assess the potential of wind energy of the area, the data were simply taken from NASA, because of the absence of full data from the NMSA. Therefore, the annual average wind speed for Axum was found to be 4.28 m/s at a height of 10 m. This value was used as the input to the wind resource in the modeling of the hybrid system. Table 3 presents the 10 years' monthly average wind speed of Axum city at the height of 10 m.

Table 3. Monthly average wind speed of Axum at the height of 10 m.

Lat 14 Long 38.7	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
10-year average	4.45	4.48	4.46	4.26	3.64	4.92	5.42	5	4.08	3.13	3.56	4.01	4.28

4.3. Load Estimation

The load estimation, which is the essential step in modeling the hybrid system, was done for a single village found in Axum district. The name of the area is Awlio, and it is around 30 km away from the existing grid found nearby, and 55 km from Adwa substation. Awlio kebele has 942 household families with a total population of 4274. One of the villages of this kebele (Kutur) has one primary school, the kebele administration office, Telecom office, a farmers training center (FTC) and one health center. The health center (HC) has midwives to help mothers deliver babies.

Moreover, HC offers support and advice to pregnant women. The load estimation for HC, FTC and kebele administration was done based on the Universal Electric Access Program (UEAP) standard [17]. The population of this village accounts for around 13% of the total population of the kebele with about 120 households.

The deferrable load contains one water pump for all households as well as the service centers that deliver public service to the community. The type of water pump is HR-14 taken from the Lorenz PS600 series, with a 300 W power rating and a pumping capacity of 40 L/m (i.e., 2400 L/h) [18]. The average daily water consumption of the community per household is 140 L/day, including the water used for their cattle. The total water consumption of the community is then 16,800 L/day. Additionally, all the service centers are assumed to use a summed average of 4000 L/day. This indicates that the overall water needed by the village is 20,800 L/day, and four water pumps of the types mentioned above are used to supply the water demand of the community. The water storage tank is assumed to have a capacity of storing water for four days (i.e., 83,200 L of water). The number of hours needed to supply the daily water consumption of the community was obtained to be approximately 2.5 h. Hence, the daily deferrable load is 3 kWh/day, and the corresponding electricity storage capacity is 10.8 kWh.

The primary load of Kutur village was calculated by considering the following: the lamps of 60 W for lighting systems with three lamps for each household; a radio receiver of 20 W; a flour mill with a rating of 15 kW; and a TV and DVD with ratings of 65 W and 20 W, respectively; but the TV and DVD are assumed to be used by the model farmers of the community. Their number is assumed to be 10% of the total households of the village. The detailed initial load estimation is as shown in Table 4. On the other hand, the load estimations for HC, FTC and kebele administration as stated earlier were taken from UEAP (which are 3 kW each) [18], because it is difficult to estimate their load based on the present condition. The total power demand for the three service centers was thus taken to be 9 kW. The daily power demand of the community, as shown in Table 4, is 51.10 kW, and the energy is 307.68 kWh without the deferrable load.

Table 4. Primary load estimation of Kutur village.

Primary Load	Single Household	No. of Households	Total No. of Equipment	Size in W for 1 Equipment	Total Power in kW	Operating hrs per Day	Energy in kWh	Remark
Lighting lamps	3	120	360	60	21.6	6	129.6	
Radio (tape recorder)	1	120	120	20	2.4	8	19.2	
TV	1	12	12	65	0.78	6	4.68	
DVD	1	12	12	20	0.24	4	0.96	
Mill	1		1	15,000	15	5	75	
Health center (HC)					3	8	24	
Farmers training center (FTC)					3	8	24	
Kebele Adm.					3	8	24	
Primary school	4	13	52	40	2.08	3	6.24	FL
		Total			51.1		307.68	

5. Modeling of the Hybrid System and Cost Analysis of Grid Extension

5.1. Modelling of the Hybrid System

As is shown in the assessment of solar radiation, Axum has a monthly average solar radiation varying between a minimum value of 5.09 kWh/m^2 and a maximum value of 7.13 kWh/m^2, with an annual average of 6.21 kWh/m^2. Similarly, the monthly average wind speed of Axum varies between 3.13 m/s to 5.42 m/s at the height of 10 m, with an annual average of 4.28 m/s. These numbers indicate that the area has a potential for implementing a PV-wind hybrid system to give electric access to the community of Kutur village of Awlio kebele found in Axum district. However, the investment costs of PV and wind turbines have always been the main barrier to the use of the hybrid system for small-scale as well as large-scale applications. However, due to technology advancement, the costs of PV systems and wind turbines are decreasing, while the price of oil is increasing in addition to the depletion of oil resources. This is encouraging developing countries like Ethiopia, which have excellent resources in both systems, to use a stand-alone hybrid system for supplying electric access to remote rural areas. The current total investment cost of PV has reached 2625 $/kW, and for that of wind, it has decreased to 1100 $/kW [19]. The current electricity grid coverage of Ethiopia is around 40%. Hence, the hybrid system can be competitive irrespective of its initial capital cost when considering the rapid increase in oil prices. Moreover, it has a negligible impact on the global and local environment. Further, solar as well as wind power are becoming serious candidates in the electricity market due to increasing oil prices and the substantial increase in manufacturing capacity of wind turbines and solar modules [20]. According to a green energy report conducted in Denmark, an estimated 23.9 GW of cells and 20 GW of modules were produced in 2010 by the solar PV industry [20]. Moreover, the total global capacity of wind power and solar photovoltaic power has reached 198 GW and 40 GW, respectively [20]. However, the PV-wind hybrid system may not be sufficient to supply energy for 24 h for the whole year, and therefore has to be supported by diesel generators and batteries, which can be used as a backup for supplying sustainable electricity when using a PV-wind hybrid system. The cost of generators varies between 200 $/kW to 1000 $/kW [21]. Therefore, in this work, the resource potential of Axum is assessed, and a PV-wind hybrid system with diesel and battery as a backup to electrify 120 households of Kutur village is modeled. Additionally, the initial capital cost of the hybrid system is compared against the cost required for extending the grid.

5.2. Cost Analysis of Grid Extension

Power is transmitted to the end-users through distribution lines. The mission of the Universal Electric Access Program (UEAP) is to deliver power to consumers in the remote rural areas of the country. It is typically done by extending the national grid from a nearby substation or an overhead medium voltage (MV) distribution line. The medium voltage levels that are most commonly used in MV line construction by the UEAP are 33 kV, 19 kV and 15 kV. Currently, the UEAP is using the 33 kV voltage level for electrifying the remote rural areas due to its advantage over the other options. The main components of an overhead distribution line that can affect the cost of grid extension are the line supports and their foundation, insulators, line accessories, conductors and overhead earth wires. The line supports can be made from wood (like local wood poles and South Africa poles), reinforced concrete poles and steel, but due to its strength and availability, UEAP is using concrete poles for MV distribution lines to give electric access for selected rural areas.

The Universal Electric Access program is currently electrifying the rural areas by extending the grid found nearby them. The main tasks done during extension are surveying, excavation, pole erection, pole top configuration and stringing of conductors. For the MV distribution line construction, all aluminium alloy conductor with a size of 95 mm^2 is used for the 33 kV line. However, the number of poles to be erected and the wire required to depend on the distance of the site from a nearby substation or MV distribution line, as well as the geographical location of the selected sites. Moreover, different accessories are used depending on the type of assemblies; these can be classified as suspension, light angle 1, light angle 2, heavy angle, T-off, tension tower and dead-end assemblies based on the angle deviation from a straight line.

Based on the theory mentioned earlier, the cost estimation for delivering electric access to Kutur village, which is found in Axum district, was performed. The distance of Kutur from an existing grid (i.e., Axum) is 30 km, and a rough survey was conducted to select the type of assemblies to be used for MV distribution line construction. This village needs 1 × 200 kVA rating transformers for supplying power to the community.

To give electric access to the 120 households, HC, FTC, flour mill, kebele administration and primary school of Kutur from the national grid found nearby, an extension of 30 km MV, 5.35 km low voltage (LV) distribution lines and erection of one transformer with a rating of 200 kVA are needed. Hence, the cost is analyzed using an interlinked spread Microsoft excel sheet used by the UEAP; the result obtained is as shown in Table 5. The total cost, as indicated in the table, includes material, transportation and labour costs, and the investment cost is therefore 5,801,286.51 Ethiopian birr, which is equivalent to 337,284.099 US dollars.

Table 5. Total cost, in Ethiopian Birr, needed for extending the grid to Kutur village of Awlio kebele found in Axum district.

Description	Salary and Wage	Allowance	Transport	Material	Total
33 kV line extension	555,518.52	678,967.08	339,100.20	2,773,182.82	4,346,768.62
1 × 200 kVA erection	2589.10	3164.46	3371.28	88,721.63	97,846.47
1 × load break switch	1516.70	1853.74	919.14	17,295.56	21,585.14
LV line extension	84,309.18	103,044.56	95,114.55	525,228.32	807,696.60
Total	643,933.50	787,029.84	438,505.17	3,404,428.32	5,273,896.83
	Interest to be capitalized				
	Over head cost (10%)				527,389.68
	Total cost				5,801,286.51
	Rechargeable/recoverable amount (**contributions*)				
	Net total				5,801,286.51

6. Results and Discussion

HOMER software was used for simulating the hybrid PV-wind system with diesel and battery storage as a backup. To get the optimal combination of the hybrid components, which could be implemented as a hybrid system model to give electric access to the community of Kutur village, the model was run for various iterations using different values of the essential variables. The diesel price was taken to be 1.1 $/L, which is the current price of oil in the country. The interest rate was also taken to be 15%, and the project lifetime was set to 25 years. Table 6 presents the various inputs to the HOMER software.

Table 6. Inputs to the HOMER software.

Item	Size	Capital	Replacement	Operation and Maintenance Cost	Sizes (kW) Considered	Quantities Considered	Lifetime
AC wind turbine (Fuhrlander 30) [2]	30 kW	33,000	24,750	660	0–4		25
AC Generator [21]	12 kW	4000	2560	0.15	0, 12, 24, 36, 48, 60		30,000 h
PV [2]	1 kW	2625	2625	0	0–100		25
Battery (S4KS25P) [12]	1900 Ah	1250	1100	25		0–100	
Converter [12]	1 kW	800	750	8	0–100		15

Results are displayed for the inputs either in the overall form, in which the top-ranked system configurations are listed according to their NPC, or in categorized form, in which only the least cost system configuration is considered for each possible combination. The variables listed in Table 6 are used as an input for simulating the hybrid set-up using HOMER. As a result, the outputs from the software are obtained in a categorized form. This is shown in Tables 7 and 8, before and after load forecasting, respectively.

Table 7. Simulation Results in the categorized form before load forecasting using HOMER.

PV (kW)	FL30	GEN (kW)	S4KS25P	Converter (kW)	Dispatch Strategy	Initial Capital ($)	Operating Cost ($/yr)	Total NPC ($)	COE ($/kWh)	Renewable Fraction	Capacity Shortage	Diesel (L)	GEN (h)
10	3	12	30	25	LF	186,750	11,714	262,470	0.402	0.92	0.09	6020	2112
	3	12	55	25	LF	191,750	12,654	273,549	0.423	0.92	0.09	5619	1941
30	3		40	25	CC	247,750	4828	278,956	0.434	1	0.1		
	1	24			LF	41,000	40,811	304,812	0.446	0.41	0.04	31,905	6000
5	1	24		5	LF	58,125	39,029	310,412	0.452	0.46	0.02	30,372	5829
10		24	5	5	CC	44,500	42,174	317,116	0.461	0.16	0.01	33,627	5147
		24	15	5	CC	30,750	47,731	339,289	0.493	0	0.01	37,798	5272
5		24		5	LF	25,125	48,983	341,758	0.501	0.08	0.06	39,062	6601
		24			LF	8000	51,689	342,128	0.512	0	0.08	41,312	6935
85			80	30	CC	347,125	5273	381,214	0.601	1	0.1		

Table 8. Simulation Results in categorized form after load forecasting using HOMER.

PV (kW)	FL30	GEN (kW)	S4KS25P	Conve (kW)	Dispatch Strategy	Initial Capital ($)	Operating Cost ($/yr)	Total NPC ($)	COE ($/kWh)	Renewable Fraction	Capacity Shortage	Diesel (L)	GEN (h)
20	4	36	45	35	LF	280,750	44,174	566,296	0.38	0.77	0.09	30,525	3726
	4	48	35	30	LF	215,750	60,989	609,989	0.398	0.66	0.05	44,411	4148
	3	48			LF	115,000	81,537	642,069	0.423	0.51	0.08	63,324	5816
10	3	48		10	LF	149,250	78,510	656,753	0.428	0.54	0.07	60,720	5639
30		48	20	10	LF	127,750	92,636	726,561	0.479	0.21	0.09	73,174	5916
35		48		20	LF	123,875	95,842	743,414	0.492	0.23	0.1	76,270	6445
		60	20	10	CC	53,000	108,470	754,167	0.484	0	0	86,354	5111
		60			LF	20,000	124,440	824,402	0.531	0	0.03	99,223	6935
20	4	36	45	35	LF	280,750	44,174	566,296	0.38	0.77	0.09	30,525	3726

By observing the few set-ups listed on the categorized form, the following results were to be found. The most cost-effective system with the lowest NPC from Table 7 is the PV-wind–generator–battery–converter set-up, where the battery operates using load following (LF), which produces only enough power to meet the demand. However, serving the deferrable load is left to the renewable resources cycle charging (CC) strategy. For this set-up, the total NPC is $262,470, and the cost of energy (COE) is 0.402 $/kWh, with a 92% contribution from renewable energy resources. Similarly, the other cost-effective option has 100% renewable resource contribution. However, the battery operates using the CC strategy, whereby the battery operates at full output power to serve the primary load, and any surplus electrical production goes toward the lower priority objectives. For this set-up, the net present cost is $278,956, and the cost of energy is 0.434 $/kWh.

On the other hand, the results from the categorized form listed in Table 8 were used to look at the other possible optimum combinations after the result of load forecasting. The first set-up containing PV-wind-Generator-Battery-Converter has a renewable resource proportion of 77%. For this set-up, the NPC is $566,296, and COE is 0.38 $/kWh, and this can also be a right choice for the implementation. The second set-up, with a 66% renewable resource contribution, which has an NPC of $609,989 and a COE of 0.398 $/kWh, can be another choice for the implementation. The contribution of monthly average electric production of PV, wind and diesel generator units for the 92% renewable resource is shown in Figure 4. In addition to this, Figure 5 shows the cost summary for the 92% renewable fraction.

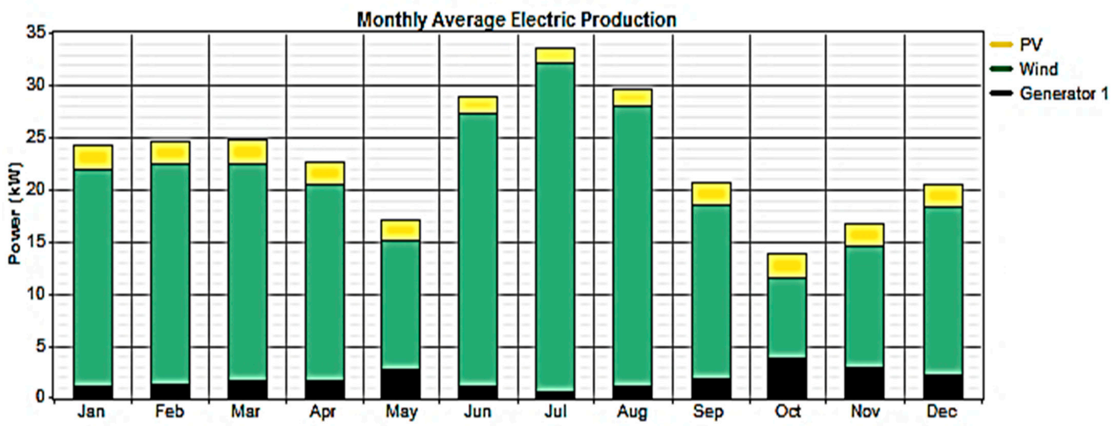

Figure 4. Contribution of the power units for 92% utilization of renewable resources.

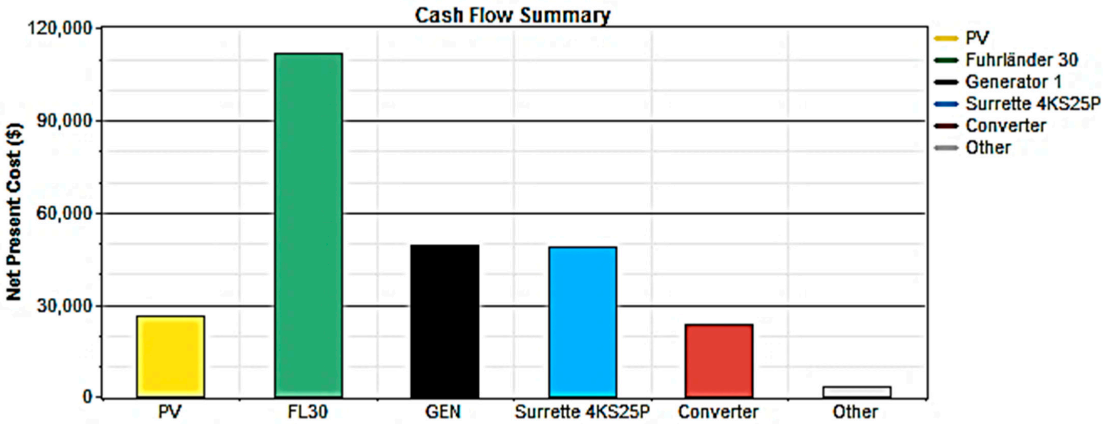

Figure 5. Cost summary for the 92% renewable resource fraction.

A bar-graph illustrates the cost breakdown for the 92% renewable fraction on the cost summary figure (i.e., Figure 5). Finally, a sensitivity analysis was carried out by varying wind speed, diesel oil price and the PV capital cost multiplier linked with the PV replacement cost multiplier. The wind speed was varied between 2.5 m/s and 4.5 m/s. The price of diesel oil is taken to be 1.1 $/litre, which is the current price within the country. Therefore, the results for this analysis are shown in Figures 6 and 7 for the respective sensitivities of wind speed to the price of diesel and PV capital cost multiplier to diesel price.

HOMER software was also used to compare the cost of the hybrid system against the cost required for extending the grid. Consequently, it was found that the hybrid system is cost-effective for an area which is found at a distance greater than 10.4 km (which is the breakeven grid extension distance) from the existing grid found nearby.

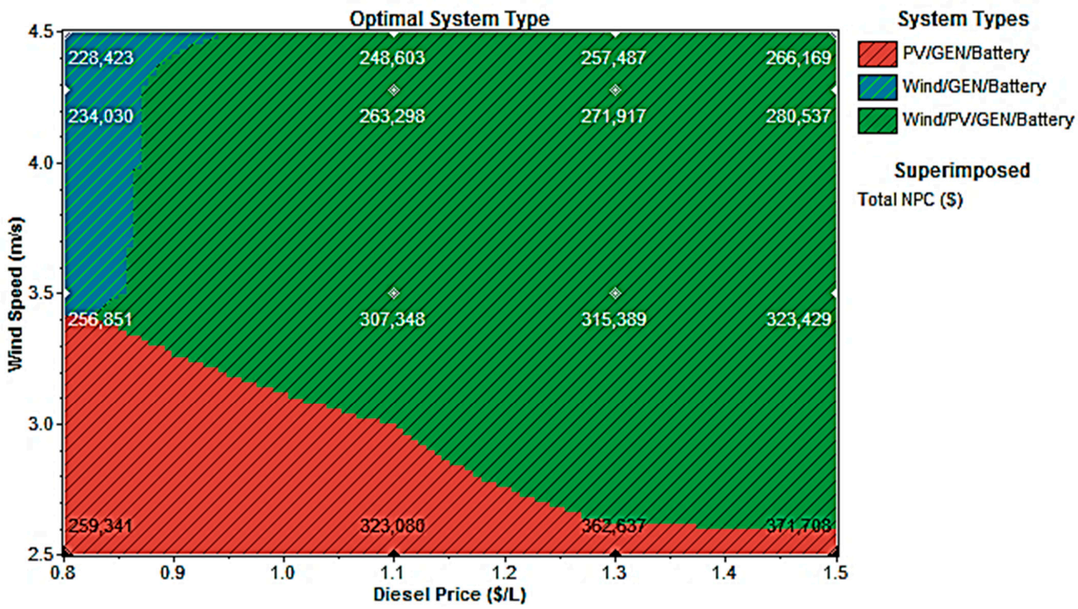

Figure 6. The sensitivity of wind speed to diesel price.

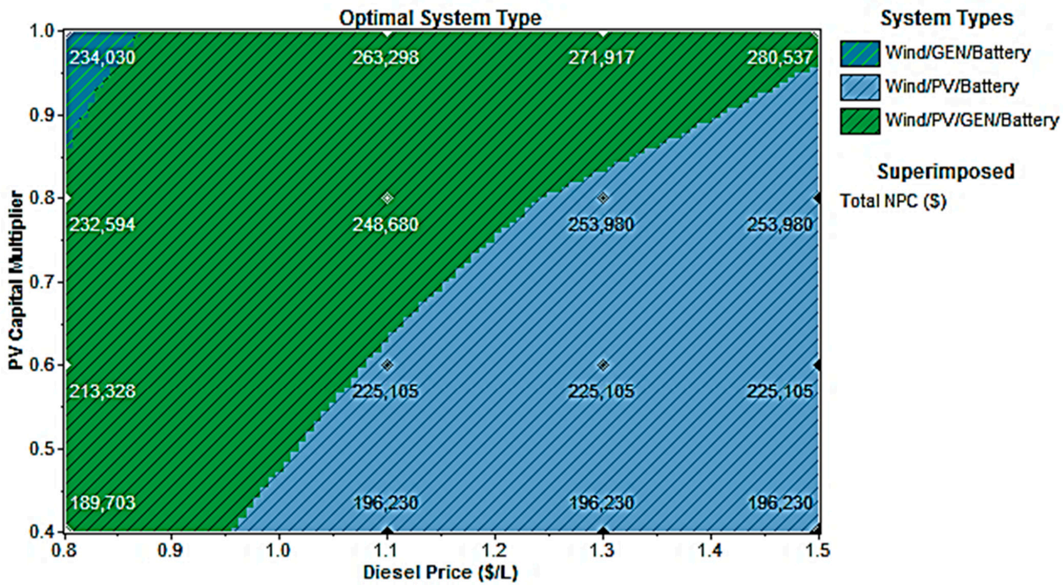

Figure 7. The sensitivity of PV cost to diesel price.

7. Conclusions

The hybrid system was simulated based on the input data gathered from the selected area, and was found to be cost-effective to use for electrifying Kutur village of Awlio Kebele found in Axum district by comparing its cost against the cost required to electrify the area by extending the national grid. The results show a number of possibilities with different levels of renewable energy resource utilization for the implementation. However, the most cost-effective system is the PV-wind–battery–converter set-up, with a total NPC of $262,470 and COE of 0.402 $/kWh. This system has an excess electricity generation of 44.6%, a capacity shortage of 8.9% and an unmet electric load of 5.2%. The other attractive set-ups from the list that can be used for the implementation are those with 92% and 100% renewable energy utilization, which have a net present cost of $273,549 and a cost of energy of 0.423 $/kWh for 92%, and an NPC of $278,956 and a COE of 0.434 $/kWh for 100%. Even though these set-ups present an increase in the NPC and COE from the first option, they are still cost-effective when compared against the cost of grid extension. For the system with 92% utilization without PV, there is an unmet electric load of 6.1%, a shortage of capacity of 9.5% and an excess electricity generation of 36.7%. Similarly, the system with 100% has an excess electricity production of 49.2% with an unmet electric load of 6.7% and a capacity shortage of 10%. On the other hand, the implementation of this system will help to reduce the deforestation caused by the community due to their dependence on firewood as well as minimize the health problems resulting from the smoke of the firewood, at the same time improving the living standard of the society of Kutur village.

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Abbreviations

CC	Cycle charging
COE	Cost of energy
EEP	Ethiopian Electric Power Corporation
FL	Fluorescent Lamp
FTC	Farmers training center
HC	Health center
ICS	Inter-Connected System
LCC	Life cycle cost
LPSP	Loss of power supply probability
LV	Low voltage
MV	Medium voltage
MV	Medium Voltage
MW	Mega-Watt
NMSA	National Metrological Service Agency
NPC	Net Present Costs
PV	Photo-voltaic
UEAP	Universal Electric Access Program

References

1. Invest in Ethiopia, Ethiopia Trade and Investment. Available online: www.ethioembassy.org.uk/trade_and_investment (accessed on 2 January 2019).
2. Drake, F.; Mulugetta, Y. *Assessment of Solar and Wind Energy Resources in Ethiopia. I. Solar Energy*; University of Leeds: Leeds, UK, 1996.
3. Dihrab, S.S.; Sopian, K. *Electricity Generation of Hybrid PV/Wind Systems in Iraq*; University Kebangsaan Malaysia: Selangor, Malaysia, 2010.
4. Barley, C.D.; Lew, D.J.; Flowers, L.T. *Sizing Wind/ PV Hybrids for Households in Inner Mongolia*; Wind Power '97; National Renewable Energy Laboratory: Golden, CO, USA, 1997.
5. Fiedler, F.; Pazmino, V.; Berruezo, I.; Maison, V. *PV-Wind Hybrid Systems for Swedish Locations*; Högskolan Dalarna: Borlänge, Sweden, 2008.
6. Mandal, S.; Das, B.K.; Hoque, N. Optimum sizing of a stand-alone hybrid energy system for rural electrification in Bangladesh. *J. Clean. Prod.* **2018**, *200*, 12–27. [CrossRef]
7. Aberilla, J.M.; Gallego-Schmid, A.; Stamford, L.; Azapagic, A. Design and environmental sustainability assessment of small-scale off-grid energy systems for remote rural communities. *Appl. Energy* **2020**, *258*, 114004. [CrossRef]
8. Zhao, P.; Xu, W.; Zhang, S.; Wang, J.; Dai, Y. Technical feasibility assessment of a standalone photovoltaic/ wind/adiabatic compressed air energy storage based hybrid energy supply system for rural mobile base station. *Energy Convers. Manag.* **2020**, *206*, 112486. [CrossRef]
9. Moner-Girona, M.; Bódis, K.; Morrissey, J.; Kougias, I.; Hankins, M.; Huld, T.; Szabó, S. Decentralized rural electrification in Kenya: Speeding up universal energy access. *Energy Sustain. Dev.* **2019**, *52*, 128–146. [CrossRef]
10. Gabra, S.; Miles, J.; Scott, S.A. Techno-economic analysis of stand-alone wind micro-grids, compared with PV and diesel in Africa. *Renew. Energy* **2019**, *143*, 1928–1938. [CrossRef]
11. Ariyo, B.O.; Akorede, M.F.; Omeiza, I.O.A.; Amuda, S.A.Y.; Oladeji, S.A. Optimisation analysis of a stand-alone hybrid energy system for the senate building, university of Ilorin, Nigeria. *J. Build. Eng.* **2018**, *19*, 285–294. [CrossRef]
12. Yeshalem, M.T.; Khan, B. Design of an off-grid hybrid PV/wind power system for remote mobile base station: A case study. *AIMS Energy* **2017**, *5*, 96–112. [CrossRef]
13. Jariso, M.; Khan, B.; Tesfaye, D.; Singh, J. Modelling and Designing of Stand-Alone Photovoltaic System (Case Study: Addis Boder Health Center south west Ethiopia). In Proceedings of the ICECA 2017 IEEE International Conference on Electronics, Communication, and Aerospace Technology, Coimbatore, India, 20–21 April 2017; pp. 168–173.

14. Jariso, M.; Khan, B.; Tanwar, S.; Tyagi, S.; Rishiwal, V. Hybrid Energy System for Upgrading the Rural Environment. In Proceedings of the 2018 IEEE Globecom Workshops (GC Wkshps), Abu Dhabi, UAE, 9–13 December 2018; pp. 1–6.
15. Duffie, J.A.; Beckman, W.A. *Solar Engineering of Thermal Processes*, 4th ed.; Wiley: New York, NY, USA, 2013.
16. Ethiopia News/GTZ Staff Magazine/August. 2010. Available online: www.enervest.de/fileadmin/downloads/gtz060810 (accessed on 5 January 2020).
17. EEPCo, UEAP. Electric Power Distribution Network Design and Construction Training Manual.
18. Final Report Country Background Information Solar and Wind Energy Utilization and Project Development Scenarios. October 2007. Available online: http://swera.unep.net/typo3conf/ext/metadata_tool/archive/download/EthiopiaSWERAreport_258.pdf (accessed on 6 December 2019).
19. Wind Power to Be Competitive with Natural Gas by 2016 Monday. 14 November 2011. Available online: http://oilprice.com/Alternative-Energy/Wind-Power/Wind-Power-To-Be-Competitive-With-Natural-Gas-By-2016.html (accessed on 8 January 2020).
20. Renewables 2019 Global Status Report. Available online: https://www.ren21.net/gsr-2019/ (accessed on 8 January 2020).
21. Hardy Diesel Generators. Available online: http://www.hardydiesel.com/diesel-generators-7-33-kw.html (accessed on 6 January 2020).