Resource Assessment and Optimal Sizing of Off-Grid Standalone Photovoltaic (SPV) System for Rural Communities in Amhara Regional State, Ethiopia

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Abstract: - Ethiopia's current population is more than 110 million people. Fifty six percent (56%) of whom live in either the rural or less urbanized areas without access to grid electricity. The use of alternative energy sources holds a promise in tackling this lack of grid electrical energy access. Standalone photovoltaic power systems, in particular, can meet the daily electrical energy demand in rural communities yet unserved by the national power grid. This paper aims to assess the solar energy potentials in the study area, and design off-grid standalone photovoltaic power systems that can provide the communities with reliable off-grid power supply. The assessment of the solar resource potential considers six widely separated areas in the Amhara Regional State of Ethiopia. Solar resource assessment showed that the annual average solar irradiation of the region is 6.46 $\mathbf{kwh/m^2/day}$ at normal tilt angle, 5.95 $\mathbf{kwh/m^2/day}$ at a latitude tilt angle, and 6 $\mathbf{kwh/m^2/day}$ at latitude plus 15 degree tilt angle. An estimate of typical household annual energy requirement indicated a consumption of 2,214.09 kWh. The design of the completed PV system includes sizing of system components and financial analyses. The financial analysis showed, the total initial investment cost will be 97,941 ETB, and for operation, maintenance and battery replacement requires of 61,770 ETB throughout the total life times of the system**.** The study demonstrated that, the designed standalone photovoltaic system yields a payback period of 13 years computed based on 3.7 ETB/kWh of energy cost. Moreover, this system will be financially feasible and, thus, encourages the use of clean energy resource of PV systems in Ethiopia.

Key-Words: - Photovoltaic system, Off-grid, Resource assessment, Load estimation, System sizing, Unit energy cost, Payback period.

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1 Introduction

The extent to which a country develops and civilizes is determined by the amount of energy its populace utilize, [1]. In productive daily human activities, energy plays a crucial, fundamental, and indispensable role. Due to the rise of worldwide industrialization and population, the scarcity of energy has become a crosscutting issue. Ethiopia is home to abundant renewable energy, particularly hydropower, wind, geothermal, and solar; yet, due to lack of energy technology and development, the reality is, it is one of the energy deficient Sub-Saharan countries.

The present population of Ethiopia of more than 110 million is the second largest in Africa, [2]. Around fifty-six percent (56%) of Ethiopians lack access to electricity, and the same proportion holds true in the Amhara Regional State. For their cooking and other day-to-day activity needs, these people in Amhara still depend on charcoal, wood, waste of crops, and other solid fuels, the use of which leads to many health-related issues that reduce their life expectancies. In addition, the use of these materials degrades the environment and contributes to carbon emissions.

In 2020 G.C, Ethiopia has a total installed power generation capacity of around 4,400 MW, about 90% (3,965 MW) of which is generated by hydroelectric power plants and 324 MW (7.65%), 7.3 MW (0.17%), and 99.17 MW (2.34%) are produced by the wind, geothermal and diesel power plants, respectively, [2]. Annual per capita electricity consumption is 100 kWh, which is much lower than the Sub-Saharan African average of 510 kWh, [3]. Roughly, the country needs to generate

6000 MW on average to cover the shortage in power.

Eighty-five percent (85%) of the people in the country live in remote, rural, and less urban areas that are geographically dispersed. Supplying them with electricity via transmission lines presents a number of problems - high capital investment, high lead time, low load factor, poor voltage regulation, and frequent power supply interruptions, among others, [3]. On-site production of electricity via generators is an alternative, but it also presents challenges of its own when considering fuel transportation - rough roads, long distances between communities, and rising fuel cost. Therefore, decentralized energy supply systems, such as standalone solar photovoltaic systems, offer the best option for rural electrification. The use of well-suited technologies of good reliability can lead to less transmission and distribution losses.

Solar irradiance reaching the surface of the earth varies with time of day, season, location, and weather conditions. Among these factors, location is a particularly major consideration in photovoltaic power system design. A standalone PV system designed for a given place may not be able to supply the same amount of load at another. Thus, a single standard will not apply as the system specification, for the same load, will vary from place to place, [1], [4].

Globally, many investigations were carried out to study the design, optimize, implement, operate, and cost-analyse off-grid SPV systems for remote household electrification, [5], [6], [7], [8], [9], [10]. The reference in [5], for example, designed and implemented a stand-alone photovoltaic system for Egyptian rural communities. The designed system is to meet the daily load demand of $2.936 kWh/day$.The 48-V PV system has a $712W_p$ (watt power), 20A charge controller, 395 Ah storage capacity and 700 W inverter. The SPV system unit cost, life cycle cost (LCC), and annualized life cycle cost (ALCC) are $\$0.201/kWh$, \$3029 and \$215, respectively. They conclude the designed PV system has the smallest unit cost compared to those in other recent studies. The reference in [6] introduced a standalone PV system used for the electrification of a conference hall in Bhopal, India. The unit energy cost is Rs28.99/kWh with $9.5kWh/day$ energy demand. The reference in [7] also carried out a techno-economic analysis of stand-alone hybrid photovoltaic-diesel-battery systems for rural electrification in the eastern part of Iran.

The reference in [8] introduced the long-term perspectives of off-grid PV system based on the system's ongoing technological improvements and cost reductions. The stand-alone PV system should cover the energy necessities for light, cooking, food conservation and electronic appliances.

The financial viability and system feasibility of stand-alone solar home systems in Bangladesh were presented in reference, [9]. The study shows the different evaluation parameters such as life cycle and energy costs, cost effectiveness, and financial indicators. The reference in [10] introduced an SPV system driving a biscuit packaging machine that requires 233.17 Ah/day. The system consisted of a total PV area of 172.23 m^2 with 315 storage batteries. Their analysis shows the system LCC is Rs15.059/kWh.

The reference in [11] investigated off-grid PV system for a typical modern house in Shewa Robit, Ethiopia. The system requires 16 modules with $130W_p$ each, 58.176 kWh storage capacity, and 3 kWh inverter to meet the annual energy consumption of 4240.936 kWh/year. The initial investment cost of the SPV system is \$12,960.36 and its unit energy cost \$0.058/kWh. The Optimal Sizing and Performance Evaluation of a Hybrid Renewable Energy System for an Off-Grid Power System was studied in [12].The reference in [13] present off-grid PV system for electrification of a single residential household in Pakistan. The peak power, capacity of battery backup, and size of charge controller and inverter were calculated to be 1928Wp, 9640.5Wh, 56.65A and 1020W, respectively. The economic evaluation using LCC analysis of the complete system has also been carried out. The LCC is found to be PKR. 457,306.

The reference in [14] compared energy payback and simple payback periods for an SPV system. The author determined that the system simple payback period ranges between 13.3 years and 14.6 years, whereas the energy payback period is estimated to be in between 1.9 years and 2.6 years. Estimates of the costs induced by additional reserve capacities to reduce the uncertainty of solar generation in the Korean power system, and analyses of the effectiveness of the Energy Storage System (ESS) in reducing these costs, using the stochastic form of multi-period security-constraint optimal power flow, were carried out by reference, [15].

In this paper, the objectives are to assess the potential of the solar power resource in the remote areas of the Amhara Regional State, Ethiopia, and, based on the resource, to design a standalone PV system to electrify these areas. The resource assessment takes into account 30 consecutive years of data at different surface tilt angles. The design and optimal sizing of SPV system components are based on the daily load demand in the area and the site's solar resource potential. Based on components available in the local market, the components are specified and their cost provided. In addition, the paper details the financial analyses of the SPV system over the life cycles of mono-crystalline PV arrays in terms of LCC, electric unit cost, and payback period.

2 Standalone PV System Design Methodology

The process of assessing the solar resource and designing a standalone PV system is subdivided into the following four main categories.

2.1 Data Collection

Data pertaining to six separate stations in Amhara Regional State, Ethiopia were collected from different sources.

(i) The data are collected from government agencies. Such as; solar radiation data are obtained from the National Meteorological Service Agency (NMSA); electrification status of the region and transmission line loss from the Ethiopian Electric Power (EEP), cost of electricity from the Ethiopia Electric Utility (EEU), and the country's future plans,energy potential, per capita energy consumption, and other relevant information from the Ministry of Water, Irrigation and Energy (MoWIE). Radiation data for a few sites not available from NMSA are sourced from the National Aeronautics and Space Administration (NASA) website.
(ii) Community electric demand and existing daily load requirement for basic, standard and modern households are obtained from site visits.
(iii) Off-grid solar PV system components rating, specifications and technological options are taken from numerous websites.

2.2 Resource Potential Assessment

Based on the solar radiation data collected, the monthly lowest and highest average solar irradiation in the region, at different surface tilt angles and measured in $kwh/m^2/day$, are assessed.

2.3 SPV System Design

The process of designing a standalone PV system involves determining the system capacity in terms of power, voltage, and current with the view of meeting the daily load requirements of a standard house. The sizing process is carried out by using the following steps, [16], [17]:

(i) Calculating the average daily solar energy input
(ii) Estimating the residential power consumption
(iii) Sizing the PV module/ array
(iv) Choosing the PV module orientation
(v) Sizing the storage batteries and specifying their configuration
(vi) Sizing the solar charge controller
(vii) Sizing the DC-AC inverter
(viii) Sizing the system cable

2.4 Economic Analyses

The economic analyses demonstrate the acceptability or feasibility of the designed SPV system. The process requires the determination of specific values: initial investment cost, storage battery bank replacement cost, operation and maintenance cost, life cycle cost (LCC), annual life cycle cost (ALCC), system unit energy cost, present values, future values, and payback period. Appropriate inflation rate, discount rate, and lifetimes are applied.

3 Result and Discussion

3.1 Resource Potential Assessment

Ethiopia is located near the equator and its solar resource is obviously significant. The annual average daily radiation in Ethiopia reaching the ground is estimated to be at 5.5 $kWh/m^2/day$, [3]. For the purpose of this study, six widely separated meteorological stations in the Amhara regional state are selected for assessing solar irradiation potential. These stations are in Gonder, Bahir Dar, Deber Markos, Debre Berhan, Dessie, and Woldia. The nearest and furthest distances between stations are 120 km and 883 km, respectively. Table 1 shows the coordinates (latitude and longitude) and elevation of each station as well as their distances from Addis Ababa and Bahir Dar. Also, in order to obtain values used in the design that closely reflect conditions in the field, solar radiation data from a 30-consecutive-year period (January 1984 – December 2013 G.C) were used.

The variation in solar irradiation monthly average, measured in $kwh/m^2/day$, at different tilt angles are shown for each station in Figure 1, Figure 2, Figure 3, Figure 4, Figure 5 and Figure 6. DNIR means solar irradiation at normal tilt angle, SIRLT at latitude tilt angle, and SIRLP15T at latitude plus 15 degrees tilt angle. Notably, the variation in tilt angles directly affects the amount of solar power that can be captured.

Bahir Dar is a special zone and the capital city of the Amhara Regional State. It is situated at the north-northwest of the country capital Addis Ababa and on the southern shore of Lake Tana, the source of the Blue Nile or Abay. Gonder is a city and separate administrative center of the Semien Gonder. Debre Markos is a city and the administrative center of the Misrak Gojjam Zone in northwest Ethiopia. Debre Berhan is a city and governmental center of the Semien Shewa Zone. Dessie is a city north of Addis Ababa and administrative center of Debub Wollo Zone. Woldia is the capital and governance center of the Semien Wollo Zone, [18].

The lowest and highest monthly averages solar irradiation are 3.95 $kwh/m^2/day$ (August, Debre Markos Station) and 8.76 $kwh/m^2/day$ (December, Gonder Station), respectively, at normal tilt angle position. Correspondingly, at latitude plus 15-degree tilt angle, the values are 4.18 $kwh/m^2/day$ (July, Debre Markos Station) and 7.63 $kwh/m^2/day$ (January, Gonder station). Similarly, at latitude tilt angle, the values registered are 4.64 $kwh/m^2/day$ (July, Debre Markos Station) and 7.02 $kwh/m^2/day$ at (January, Gonder Station).

The annual average solar irradiation of the region is 6.46 $kwh/m^2/day$ at normal tilt angle, 5.95 $kwh/m^2/day$ at a latitude tilt angle, and 6 $kwh/m^2/day$ at latitude plus 15 degree tilt angle. For this design, the highest value of average solar irradiation (6.46 $kwh/m^2/day$) is used for satisfying the power demand throughout the year in all stations with a latitude tilt angle orientation.

Table 1. Station coordinates and elevation above sea level

Station	Coordinates	Elevation (in meters)	Distance from Addis Ababa (in km)	Distance from Bahir Dar (in km)
Bahir Dar	11° 59' N, 37° 39' E	1,800	570	-
Gonder	12°6′ N, 37°46′E	2,133	758	188
Debre Markos	10° 35' N, 37° 73' E	2,446	295	275
Debre Berhan	9° 67' N, 39° 53' E	2,840	130	700
Dessie	11°13′N, 39°63′E	2,470	401	480
Woldia	11° 83' N, 9° 68' E	2,112	520	360

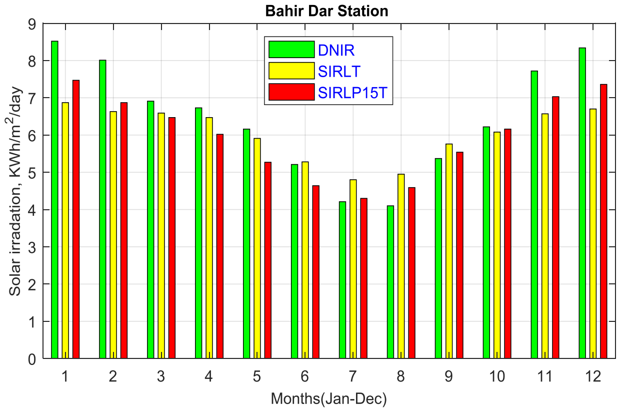

Fig. 1: Solar irradiation in Bahir Dar Station at normal, latitude, and latitude plus 15 degrees tilt angles

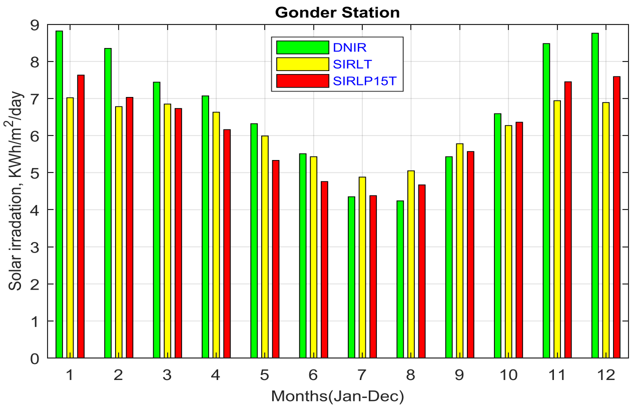

Fig. 2: Solar irradiation in Gonder Station at normal, latitude, and latitude plus 15 degrees tilt angles

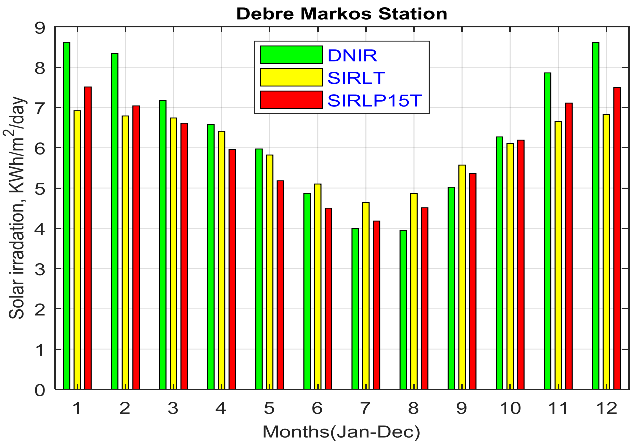

Fig. 3: Solar irradiation in Debre Markos Station at normal, latitude, and latitude plus 15 degrees tilt angles

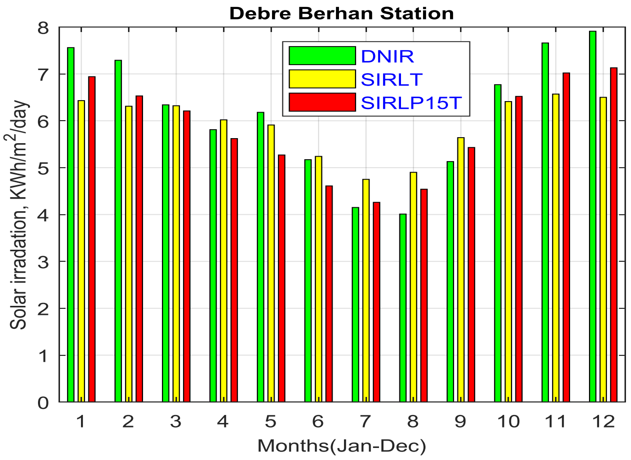

Fig. 4: Solar irradiation in Debre Berhan Station at normal, latitude, and latitude plus 15 degrees tilt angles

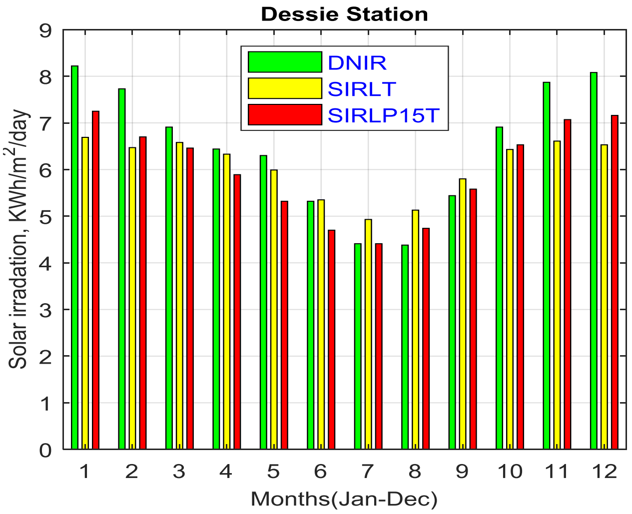

Fig. 5: Solar irradiation in Dessie at normal, latitude, and latitude plus 15 degrees tilt angles

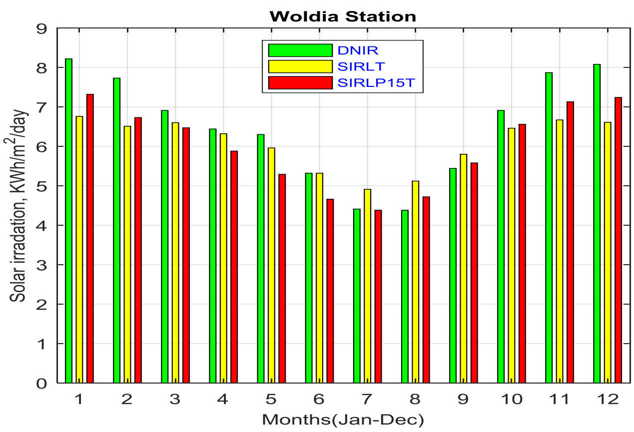

Fig. 6: Solar irradiation in Woldia Station at normal, latitude, and latitude plus 15 degrees tilt angles

3.2 Household Daily Load Estimation

The entire solar PV system design is based on the size of the load and the available solar irradiation resource. Thus, the design of a solar PV system begins with the calculation of the daily energy consumed. Inaccurate load calculation may lead to a system failure or a high loss of load probability, [19]. If the bases of load calculation are inaccurate, either the initial cost will be too high or the battery and array/module sizes be too small so as to cause the system to fail eventually.

Above 98% of the people who live in the Amhara Regional State rural area are farmers. The variation in land and water availability, transportation access, weather condition, among others, result in farmers having different standards of living. In this study, the farmers are classified based on certain levels of standard of living: 1) Basic Level - represents poor farmers; 2) Standard, or Middle, Level – contains average class farmers, and 3) Modern, or High, Level - consist of farmers who have very good economic capacities. The present SPV design caters to households belonging to farmers in the Standard and Modern Levels, they being in a category of households that has the capacity to invest in an undertaking of this magnitude. The design of an SPV system for households at the Basic Level will entail a different set of requirements, and putting up the designed system will need financial assistance from the government. Most of the people who live in the middle and high levels have three structures, buildings, or shelters on their premises. The first structure, which has an area of between $25m^2$ and $35m^2$, is used as enclosure for animals, kitchen, and store. Its roof is covered with grass and hull and circular or rectangular in shape. The second is used for dining and sleeping, and its area, commonly $42m^2$, $56m^2$, or $72m^2$, depends on the number of people who lives in it. The last consists of toilet and bathroom. The household electric devices and their corresponding daily energy requirements are listed in Table 2 and Table 3, respectively. Based on these tables, the following values are arrived at:

- Total household power requirement per day (P_T) =3.948 kW
- Total household daily energy consumption = 6.066 kWh
- Total household annual energy consumption = 2,214.09 kWh

Table 2. Lighting loads

Lamp placement	Qty	Power rating per lamp (W)	Total power (kW)	Operating hours per day (h)	Energy required per day (kWh/day)
Dining (Salon) room	2	11	0.022	3	0.066
Master bedroom	1	11	0.011	1	0.011
Children's bedroom	1	9	0.009	5	0.045
Outdoor	2	9	0.018	3	0.054
Kitchen	1	7	0.007	2	0.014
Toilet and bathroom	2	5	0.01	1	0.01
Animal living room	1	11	0.011	1	0.011
Total			0.088		0.211

3.3 System Design

The design of standalone PV system is a process of putting together all the different electrical components sized correctly and economically to generate electricity from sunlight and satisfy the daily energy requirement without interruption even during autonomy days, [1]. The components include solar PV modules, charge controller, batteries, DC to AC inverter, protective device and system wiring.

The designed SPV system is applicable for implementation anywhere in Amhara Regional State, Ethiopia. As shown in the solar resource assessment, all the stations have closely similar solar irradiation patterns throughout the year, especially in the summer season, and slight differences in the winter season. To reduce to the lowest possible value the required number of PV modules and storage batteries, the most efficient available components are selected. 48 V DC is the selected nominal system voltage (V_S).

Table 3. Appliance loads

Appliance	Qty	Power rating per appliance (W)	Total power (kW)	Operating hours per day (h)	Energy required per day (kWh/day)
Stove	1	1000	1	2	2
Electric Mitad	1	2500	2.5	0.05	0.125
Refrigerator	1	100	0.1	24	2.4
Boiler	1	100	0.1	1	0.1
Radio	1	20	0.02	4	0.08
TV(21'')	1	100	0.1	7	0.7
DVD /VCD player	1	30	0.03	7	0.21
Telephone	2	10	0.01	24	0.24
Total			3.86		5.855

3.3.1 Sizing of PV Array

The PV array is one of the key components of off-grid PV system. The power generated by the PV array must be enough to meet not only the required daily energy consumption as shown in Table 2 and Table 3 but the system losses as well. To size the array, there is basic information required: insolation in the given location, module efficiency, module temperature coefficient (T_{CF}), voltage loss in cables, and battery, inverter, and charge controller efficiencies, [4], [5], [11]. The PV module derating factor (D_F) accounts for the dirt or dust that accumulates on the PV module surface over time and reduces its effectiveness to generate power. The PV module surfaces will thus require periodic cleanup as part of maintenance. In this paper the following values are applied: 21% PV module efficiency (η_{pv}), [20], 98% charge regulator efficiency(η_{cc}), [21], 93% inverter efficiency (η_{inv}), [22], 90% battery efficiency(η_B), [23], 0.98 D_F [11], 3% cable loses (η_{cab}), and unity temperature coefficient factor (T_{CF}), [24], because at all stations the temperature is above standard. From these parameter values, the total power that the PV array must generate is determined by using equation (1) [19]. Peak sun hours (H_{PSH}) is the ratio of the average solar irradiation at the site (6.46 kwh/m^2/day) to standard power generated by the PV module (H_s) as $1\,KW/m^2$ at 25 ℃ , [25] . As per equation (1), [26], the minimum required power the PV array needs to generate is 5.74 kW per day.

$$P_g = \frac{E_{DEC}}{H_{PSH} \times D_F \times T_{CF} \times \eta_T} \quad (1)$$

where P_g= the total power generated by SPV array, E_{DEC}= daily energy consumption, and η_T = total efficiency = $\eta_{inv} \times \eta_{pv} \times \eta_{cc} \times \eta_B \times \eta_{cab}$

Mono-crystalline, polycrystalline and thin-film solar cells are the most common type of solar cells and they differ in the type of silicon used, manufacturing process, and product quality. In this work mono-crystalline KFM275M-20 PV modules are used because they cost less and are available in the local market. The technical specification for this module is shown in Table 4.

Table 4. KFM275M-20 PV module technical specification, [20]

Parameters	Values
Module Type	KFM275M-20
Power rating	275 W
V_{OC}	38.3 V
I_{SC}	9.49 A
I_{MP}	8.76 A
V_m	31.3 V
Module Efficiency	21.5 %
Mono solar cell	156x156mm (60 pics)
Power tolerance	0-5%
Maximum system voltage	1000 V
Power temperature coefficient	-0.3%/℃
Dimensions (lxwxh)	1640x992x35mm
Weight	19.5 kg

The total number of modules (T_{NPM}) required to supply the daily energy need of a standard home is 20 modules per equation (2). P_{SMP} represents the selected module rated power.

$$T_{NPM} = \frac{P_g}{P_{SMP}} \qquad (2)$$

Those modules must be so connected as to obtain the specified system voltage. Thus, a number of modules are connected in series to form a string and a number of strings in parallel to obtain the overall rated current and voltage of the array. The number of modules connected in series (T_{MS}) to form a string and the number of strings in parallel (T_{MP}) are calculated using equation (3) and (4), respectively.

$$T_{MS} = \frac{V_S}{V_M \times D_F} \qquad (3)$$

$$T_{MP} = \frac{T_{NPM}}{T_{MS}} \qquad (4)$$

Based on the calculation T_{MS} = 2 and T_{MP}= 10, which mean two modules will form a string and ten of these strings will connect in parallel to yield a maximum charging current of 10 strings times 8.76A per string or 87.6 A.

3.3.2 Sizing of Storage Capacity

The storage capacity should be enough to store sufficient energy to power the household loads for the specified period at night time and on cold days and rainy seasons. The battery chosen for this design is 3TT200, and its technical specification is shown in Table 5. To determine the required number of the specified battery, the days of autonomy (D_A), efficiencies of inverter and battery, and maximum allowable depth of discharge (DOD) must be considered carefully. The days of autonomy is the number of days the standalone PV system can operate without sunshine. Its value for a design purpose is usually three to five days, [4], [11], [17], [23]; 3 days is used in this design. The required battery capacity (S_C) is determined as in equation (5).

$$S_C = \frac{E_{DEC} \times D_A}{DOD \times \eta_{inv} \times \eta_B} \qquad (5)$$

From this equation, it can be shown that the storage capacity required for the given household load and parameter values is 27.161 kWh. Calculation of the ampere-hour storage capacity (S_{Cah}) of the battery bank using equation (6) gives us 556Ah.

$$S_{Cah} = \frac{S_C}{V_S} \qquad (6)$$

Table 5. 3TT200 battery technical specification, [23]

Parameters	Values
Type of battery	3TT200
Nominal voltage (V_{SB})	12V
Capacity @ C-10	200Ah
Depth of discharge (DOD)	80% for 1500 cycles 50% for 3000-5000cycles
Efficiency	90%
Dimension (lxwxh)	500x187x450mm
Self-discharge	Less than 3% per month
Weight	44.7kg
Service life under	6-10 years

A number of batteries (N_{BS}) has to be connected in series to meet the system voltage specification; a number of this series connections (N_{BP}) are then connected in parallel to meet the current specification. $N_{BS}$and N_{BP} are found using equations (7) and (8), respectively, [26].

$$N_{BS} = \frac{V_S}{V_{SB}} \qquad (7)$$

$$N_{BP} = \frac{S_{CAh}}{C_{BS}} \qquad (8)$$

where, V_{SB}= nominal voltages of selected battery C_{BS} = ampere-hour storage capacity of selected battery. Hence, the total number of batteries needed to store the energy for the given 3 days of autonomy can be calculated as in equation (9).

$$N_T = N_{BS} \times N_{BP} \qquad (9)$$

Thus, from Equations 7, 8, and 9, we find that 3 battery strings connected in parallel, with each string having 4 batteries connected in series, are needed to ensure the system bus voltage and current. All in all, the storage battery bank will use twelve 3TT200 batteries.

3.3.3 Selection of Solar Charge Controller

The main role of charge controller in a standalone PV system is to protect the batteries from over-charging and over-discharging which can lead to battery damage. The maximum load current (I_{Lmax}) capacity is determined by using equation (10).

$$I_{Lmax} = \frac{P_T}{V_S} \tag{10}$$

The maximum charging current capacity (I_{CCmax1}) can be calculated from the equation$I_{CCmax1} = T_{MP} \times I_{MP}$. The controller must also be capable of carrying the PV array short-circuit current (I_{CCmax2}), which can be determined from the equation $I_{CCmax2} = 1.3 \times I_{SC} \times T_{MP}$. $I_{MP}$and I_{SC} represents the maximum current at maximum power and short-circuit current of the selected PV module respectively. The design current should be the larger of the two. Thus, the rating of the selected charge controller must be equal or greater than 87.6A/48V. The selected charge regulator should fully meet not only the system operating voltage and maximum charge current capacity but also the maximum load current capacity, reverse leakage current, high and low voltage disconnect set point, and operating ambient conditions as well, [19]. Consequently, the maximum power point tracking charge regulator whose technical specification is shown in Table 6 is selected. The selected charge controller has a battery charge indicator, storage level indicator, load indicator, power reset point, and terminals for connecting the storage battery bank, PV array, and DC loads.

3.3.4 Sizing of DC- AC Inverter

The inverter is used to convert DC power stored in the battery to AC power. Its sizing is based on surge capability, continuous power output, efficiency, waveform, input DC voltage, output AC voltage, frequency and voltage regulation, [19]. From equation (11), the inverter power rating (P_{inv}) is 4.245 KVA at unity power factor (PF).

$$P_{inv} = \frac{P_g}{PF \times \eta_{inv}} \tag{11}$$

Table 6. Charge controller technical specification, [21]

Parameters	Value
Type	MPPT
Operating Voltage	48V
Charging current	100A
Efficiency	98-99.5%
Enclosure protection class	IP43
Operating temperature	0℃- 55℃
Heat dissipation	Self-cooling
Dimension (lxwxh)	406x314x128 mm
Weight	7.1 kg

The power rating of the selected inverter should be greater than 10%-25% than this calculated power, [5], [11]. Thus, using a compensation of 20%, an inverter rated at about 5.094 KVA is selected. The technical specification for the selected 5 kVA inverter is shown in Table 7.

Table 7. Inverter technical specification, [22]

Parameters	Values
Model	Sprit 5KVA+SCC
Rated output power	5KVA
Output voltage waveform	Pure sine wave
Output voltage	230Vac±5%
Output frequency	50 Hz
Efficiency	93%
Nominal DC input Voltage	48V
Overload capability	110-150 % load for 10s >150% loaded for 5s
High DC cut off voltage	58 V
Low DC cut off voltage	40

3.3.5 System Cable Sizing

The design of a SPV system is incomplete until the correct size and type of cable is selected for interconnecting the system components together, [1]. Different cable sizes are used in different parts of the SPV system like PV array to charge the controller, battery to charge controller, battery to inverter, and AC distribution board to load.

3.3.5.1 PV Array to Charge Controller Cable

The wire joining the PV array to the charge controller should be able to resist sunlight and water as well as mechanical damage, [19]. The size of the wire depends upon the allowable voltage drop, the current flow, and the wiring length between the PV array and the charge controller. Most of the time, PV arrays are installed on the roof of the house. Here, the cable length is assumed to be ten meters. The percent voltage drop along the length of the wire must be reasonably less than 10% of the system voltage (V_S), [4], [11], [19]. Accordingly, with a wire length (L_C) of 10 m, voltage drop (ΔV) of 4%, and array current (I_{max}) of approximately 88A, the minimum cross sectional area of the wire (A_W) is $50\boldsymbol{mm^2}$ as computed from equation (12).

$$A_W = \frac{0.3 \times L_C \times I_{max}}{\Delta V} \qquad (12)$$

3.3.5.2 Battery to Charge Controller Cable

The size of the wire connecting the charge controller and the battery is also calculated by using equation (12). However, ΔV, LC, should be taken as 1% and 5m, respectively, while the current should be the largest value that can flow through the wire. During the charging process, the current flowing through the wire is similar to the current received from the PV arrays while during the discharging process the current is equal to the total load current. The largest current flow through the wire during charging and that is 87.6A. Calculating, the minimum cross-sectional area of the wire would then be $50\boldsymbol{mm^2}$. The same wire size is used for connecting the storage battery bank to the inverter.

A similar calculation is carried out for the size of the cable connecting the AC distribution board to the loads. The wire must be no less than 4 mm^2 in cross sectional area, considering wiring length of 50 meters and a voltage drop of five percent.

3.4 Financial Analyses

Unit energy cost and payback period are the two basic indicators of the project feasibility, and life cycle cost (LCC) analysis is the most valuable statistical tool for evaluating the economic behavior of renewable energy systems, [5]. The LCC analysis cover all the system's life stages: initialization stage, operation and maintenance stage, and replacement stage, [27], [28], [29], [30]. In the initial stage, the initial investment cost required to setup the system is incurred and includes the expenses for purchasing the PV array, charge controller, storage batteries, inverters, switch, lamp, breaker, distribution board, and cable and installation costs as shown in Table 8. Operation and maintenance stage expenses are periodical expenditures for the regular maintenance, operation, and management of the system. Replacement stage expenses are those incurred for replacing storage batteries, which may not regularly happen, to ensure continuous, proper, and efficient operation of the system. Depending on the battery type and operating condition of the storage batteries in the PV system, batteries may be replaced every six to ten years, [4], [5], [23]. The expected lifetimes of PV modules are estimated to be between twenty and thirty years, [31], [32]. For the current design, the lifetimes of the PV module and battery are twenty-four and eight years, respectively. The storage batteries will thus need to be replaced two times, on the eighth and sixteenth year, during the 24-year life of the system.

Table 8. Initial investment cost

No.	Items	Qty	Unit price (ETB)	Total (ETB)	Remark
1	PV module	20	1,800	36,000	As per Table 4
2	Battery	12	2,500	30,000	As per Table 5
3	Charge controller	1	8,000	8,000	As per Table 6
4	Inverter	1	13,968	13,968	As per Table 7
5	Cable				
	SPV to charge controller	10 m	45/m	450	
	Battery to charge controller	5m	30/m	150	
	Battery to inverter	5m	30/m	150	
	AC distribution board to load	50 m	15/m	750	
6	Switch	7	30	210	
7	Installation cost			3,600	10%PV cost
8	Other equipment's			4,663	5% total cost
	Total investment cost			97,941	

Inflation and discount or interest rates should be considered when making future estimations of costs associated with off-grid PV systems. The inflation rate represents the decrease in the value of money over time, while the discount rate represents the increase in the value of money with time due to interest, [19]. Currently, the Commercial Bank of Ethiopia interest rate (r) is seven percent. The inflation rate (f) of the country is taken as five percent. In this study, it is taken that operation and maintenance ($Q_{O\&M}$) and installation (Q_I) costs are two and ten percent, respectively, of the PV investment cost (Q_{PV}). The first battery replacement cost ($Q_{B@8}$) is 25,731 Ethiopian birr (ETB) by equation (13), and second replacement cost ($Q_{B@16}$) is 22,071 ETB as per equation (14), [5].

$$Q_{B@8} = Q_B \left[\frac{1+f}{1+r}\right]^8 \qquad (13)$$

$$Q_{B@16} = Q_B \left[\frac{1+f}{1+r}\right]^{16} \qquad (14)$$

Hence, the total battery replacement cost required over 24 years is 47,802 ETB and the operation and maintenance cost is 13,968 ETB as per equations (15) and (16), respectively[4]. In equation (16), Y represents replacement years.

$$Q_{RBT} = Q_{B@8} + Q_{B@16} \tag{15}$$

$$Q_{O\&M} = 0.02\, Q_{PV}\left[\frac{1+f}{1+r}\right]\left[\frac{1-\left(\frac{1+f}{1+r}\right)^{Y}}{1-\left(\frac{1+f}{1+r}\right)}\right] \tag{16}$$

The system life cycle cost can be calculated by adding the initial investment, operation and maintenance, and battery replacement costs as in equation (17).

$$LCC = Q_{IIV} + Q_{RBT} + Q_{O\&M} \tag{17}$$

The annual life cycle cost (ALCC) is estimated from equation (18) [28].

$$ALCC = LCC\left[\frac{1-\left(\frac{1+f}{1+r}\right)}{1-\left(\frac{1+f}{1+r}\right)^{Y}}\right] \tag{18}$$

As calculated from equations (17) and (18), the system LCC is 159,711 ETB and the ALCC is 8,225 ETB. The unit electrical cost (Q_{UE}) is 3.7 ETB/kWh as per equation (19), [28].

$$Q_{UE} = \frac{ALCC}{365 \times E_{DEC}} \tag{19}$$

For calculating the payback period, total investment cost, annual income and annual expenditure must be considered [16], [19], [27]. Based on this, the investment recovery period is 12.8 years. Figure 7 shows the designed system component percent cost distribution over a 24-year life cycle.

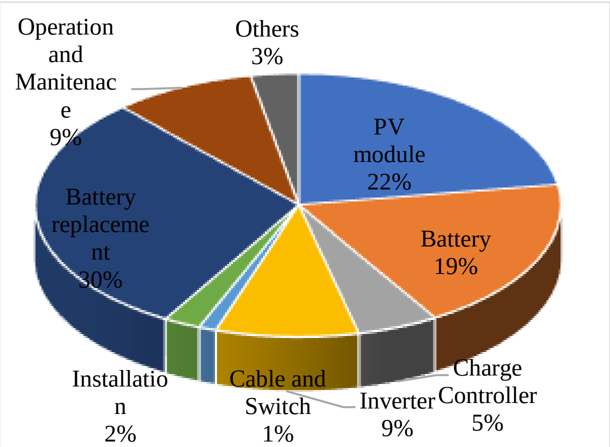

Fig. 7: The designed system component percent cost distribution over a 24-year life cycle

This implies the power system will return its investment cost within 12 years and 8 months at a unit energy cost of 3.7 ETB/kWh. The results of the economic analysis shows, this project is feasible.

4 Conclusions

This study focuses on assessing the solar energy resource potential and designing a standalone solar photovoltaic system that matches the given solar resource and the specified load so as to provide electricity for rural, remote areas where access to the utility grid is nonexistent. The solar energy resource potential of the Amhara Regional State is investigated using 30-year data from the region's six geographically and widely separated stations considering different tilt angles. Based on the irradiance data, Gonder Station has relatively higher solar irradiance while Debre Markos and Debre Behan Stations have relatively lower irradiance.

The study has shown that a standard and modern household with a daily load of 6.066 kWh/days and an annual average solar irradiance of 6.46 $kWh/m^2/day$ can be served by an SPV system having twenty KFM275M-20 modules with a total power generation capacity of 5.74 kW, twelve 3TT200 batteries each rated at 12V and 200Ah, a 100-A/48-V MPPT charge controller, and a 5-kW inverter.

The economic analyses of the off-grid photovoltaic system shows that the system needs 97,941 ETB initial investment, 47,802 ETB for battery replacement, and 13,968 ETB for operation and maintenance, on the basis of 24 years of PV array and 8 years of battery lives, 5% inflation rate, and 7 % interest rate. The analyses also show that the system life cycle cost is 159,711 ETB, the annual life cycle cost is 8,225 the unit energy cost is 3.7 ETB/kWh, and the payback period is 12.8 years. The analyses thus indicate that the system is feasible. Though the initial investment cost of the SPV system is high, the amount can be recovered within approximately thirteen years and the system is usable for more than 24 years without power interruption and bills. Finally, the standalone photovoltaic power system can provide access to electrical energy that hasn't access to grid electricity approximated around 56% of the Ethiopian people.

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