Incidence of load profiles in the Levelized Cost of Electricity for a solar-PV generation system located in Lambayeque-Perú.

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***Abstract*– In this research work, a comparative cost analysis of electricity produced by a renewable energy system is carried out considering two reference electric load profiles. A 165.4-kWh daily electric load is established on the basis of a community-type profile, with a 20.5-kW peak load and a load factor of 0.34.**

Using simulation built-in features from HOMER Pro, optimum sizing for both a load profile driven by night-time energy demand and a load profile driven by day-time energy demand is carried out. A proposed solar-PV generation system, for a load driven by night-time energy demand, consists of an 81.5-kW solar PV generation system, a 657-kWh storage capacity, and a 44.87-kW DC-AC converter. On the other hand, a proposed solar-PV generation system, for a load driven by day-time energy demand, consists of a 103-kW solar PV generation system, a 443-kWh storage capacity, and a 29.2-kW DC-AC converter.

A levelized cost of electricity (LCOE) approach is used for comparison purposes. Also, net present cost (NPC) is calculated for the proposed energy supply alternatives.

It is concluded that for comparative cost analysis key aspects, such electric load profile and its correlation with solar radiation availability on hourly basis, play a significant role. Also, Demand-Side Management and End-Use Energy Efficiency would further contribute to optimize the sizing of solar-PV generation systems.

Keywords—Solar Energy, Clean Technology, Cost Analysis, Environmental Sustainability.

I. INTRODUCTION

Energy supply based on renewable resources is gaining an increasing attention worldwide. According to different references, Peru is considered to have high solar radiation levels compared to other regions in the world. Also, prices for fossil fuels in Peru are considered similar to international levels if not slightly higher. Besides, environmental concerns associated with the use of fossil fuels for electricity supply, in locations not yet connected to main electric grid, are getting more attention in many regions.

In this research work, a reference electric load located in Lambayeque will be considered for simulation purposes. Lambayeque region is located on the northern coastal region of Peru.

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II. BACKGROUND

According to Ref. [01], HOMER stands for Hybrid Optimization Model for Electric Renewables. Midwest Research Institute has the copyrights of this software. It was developed by National Renewable Energy Laboratory (NREL) of United States. It is used to help the designing of various power plant configurations. It has different built-in components in it such as PV panels, Wind turbines, Utility loads of various kinds, Generators, Converters and Battery Backup etc. It is used to simulate various schematics of power plants and then those schematics are simulated to find most optimized power plant configuration with respect to operating cost, net present cost (NPC), gases emission and economic comparison etc. The demand of electricity is increasing throughout the world. Needed to design some innovative new renewables energy systems which can decrease the dependence on conventional energy resources. Analyzing different cases and according to these cases we can evaluate their power generation, pollutant gases emissions, net present cost and average electrical production cost are estimated using HOMER Pro software.

According to Ref. [02], the article contains the average daily electric load pro- file (for 24 h of the day) for the five categories of residential buildings (duplex, single family bungalow, traditional court yard, flat/apartment dwelling and 'face-me-I-face-you') in Nigeria. In each one, 10 buildings per residential building type were surveyed for the collection of data with the aid of a questionnaire. In each surveyed household, a household member completed the energy audit section of the questionnaire with the assistance of the questionnaire administrator while the section of the questionnaire designed as a time-of-use diary was left with the household for completion. For each building surveyed, the data retrieved from the completed time-of-use diary was used in Microsoft Excel for computing the hourly electricity load profile for the seven days of the week. In order to obtain the hourly energy load (in watts) for each building, the power rating of the appliances used during each of the 24 h of the day was summed and the result in watts was converted to kWh by dividing by 1000. Each dwelling's daily load profile was obtained as an average of the load profile for the seven days of the week. The article as well provides data on the solar photovoltaic systems' components designed to supply electricity to the building and the levelized cost of electricity

(LCOE) of the systems for the base case scenario and different sensitivity cases obtained from simulations using HOMER Pro. The load profile data provided in this article can be reused by other researchers in the design of solar photovoltaic systems for residential buildings.

According to Ref. [03], the study evaluated the outcome differences when adopting five different solar irradiation databases on the sizing of hybrid solar photovoltaic-diesel generators designed to supply electricity to isolated mini-grids. To do this, the two most widely adopted photovoltaic (PV) simulation packages in the market, namely PVsyst® and HOMER Energy® were used. The different origins, data timespan, space and time resolution, of the five most relevant solar irradiation databases available for the region were compared. A case study was presented to illustrate the influences of the solar irradiation database and the solar simulation tool on the resulting PV generator. Furthermore, the hourly behavior of the energy supply to an existing load in a mini-grid in the Brazilian Amazon was evaluated, together with the savings in diesel obtained with the resulting PV generator. Evaluating the five options of solar radiation databases, for the same PV plant configuration, variations of up to 19.7% were found in the expectation of PV generation. When the simulation software package was varied, the combined effect (radiation database X PV system sizing tool) showed differences of up to 20.6%. This demonstrates that despite having different algorithms, computational tools have a small influence (less than 1%) on results. These combined differences, taking into account the load curve behavior and the total diesel generation capacity installed at the site, resulted in over 100% differences in the optimum PV generator size in the case study. The total savings in diesel fuel, over a 15-yr period, ranged from $6.5 million to over $16 million (> 2.5 times) for the smallest PV system. This demonstrates the importance of the correct choice of database. These evaluations can be extended to mini-grids of any size elsewhere. The novelty and originality of this study is to demonstrate and quantify for the first time the influence of the solar radiation database and the PV simulator package on the sizing of PV-diesel generators. The consequences of this study are not only of scientific and academic importance, but of economic and commercial interest as well.

According to Ref. [04], this research proposes, through HOMER, to evaluate the technical and economic feasibility of a hybrid energy system, taking advantage of solar and wind resources in a remote community in Haiti. Several configurations were analyzed, the most viable has a net present cost (NPC) of US$ 389,647 and US$ 0.497/kWh of energy cost (COE). It could produce 82,124 kWh/yr and 0% of unmet annual load. This configuration still has 9.6% excess electricity, which is important for a possible increase in load. A sensitivity analysis was performed, which shows the performance and technical feasibility of the system for future load increase.

According to Ref. [05], stand-alone solar photovoltaic (SA-SPV) systems are attractive options for rural electrification programs in many countries. These systems are invariably provided with battery energy storage (BES) for using stored electricity during nighttime. Availability of bi-directional power electronic converter promises to enhance application of these SA-SPV systems for generating, storing and feeding electricity to local micro-grids. Further, the advantages of such systems can be maximized by minimizing energy losses at different sub-system levels in the system. In the present work, we demonstrate use of HOMER Pro simulation software for simulation of energy performance of SA-SPV (6.75 kWp) system installed in Renewable Energy Systems Laboratory in our Institute, aiming at quantitative estimation of energy losses due to stand-alone mode of operation. The system is provided with battery energy storage (800 Ah) that is used for supplying electricity for night time street lighting on campus up to eleven hours per day. The results of simulation show that when the existing SA-SPV system is upgraded to grid-tied SPV system, by incorporating bi-directional converter, the system will produce total 11086 kWh annually at the site, out of which 4536 kWh will be fed to the local single-phase micro-grid, which accounts for energy lost if the system continues to operate as SA-SPV system.

According to Ref. [06], the interest of power is expanding step by step all through the world. Because of constrained measure of fossil fuel, it is vital to outline some new non-renewable energy frameworks that can diminish the reliance on ordinary energy asset. A hybrid off-grid renewable energy framework might be utilized to reduction reliance on the traditional energy assets. Advancement of crossover framework is a procedure to choose the best mix of part and their cost that can give shabby, solid and successful option energy resource. In this framework, the essential wellspring of power is sun based solar photovoltaic system and biomass gasifier generator set while fuel cell and batteries are utilized as reinforcement supply. HOMER simulator has been utilized to recreate off the grid and it checks the specialized and financial criteria of this hybrid energy system. The execution of every segment of this framework is dissected lastly delicate examination has been performing to enhance the mixture framework at various conditions. In view of the recreation result, it is found that the cost of energy (COE) of a biomass gasifier generator set, solar PV and fuel cell crossover energy system has been found to be 15.064 Rs/kWh and complete net present cost Rs.51,893. The abundance power in the proposed framework is observed to be 36 kWh/yr with zero rates unmet electrical burden.

According to Ref. [07], it shows the approach to the design aspects of a hybrid energy system that will target educational institutes. The purpose of this work is the computation, simulation & optimization of hybrid energy system. The hybrid energy system comes from the biomass gasifier generator set, solar and fuel cell with battery storage system to fulfill partially load requirement of Energy Centre, MANIT Bhopal. The computation software used for this work is HOMER Pro 3.2.3. HOMER Pro is a design simulation model that analyzed the sizing, costing optimization and control strategy of the hybrid energy system. The analysis of such hybrid energy systems feeding AC primary load of 101 kWh/day energy consumption with a 5-kW maximum load demand. The simulation results show that optimized size of components, biomass gasifier (5 kW) – solar (5 kW) – fuel cell (5 kW) and optimized cost of energy about 15.064 Rs/kWh.

III. Methodology

A proposed methodology for this study is based on determination of local electric demand patterns, considerations for project lifetime and economics, and sizing of a solar-PV system, followed by a comparison of electricity generation cost.

A. *Electric Power and Energy Demand*

It is rather important to distinguish between Power and Energy requirements. Therefore, with regard to electricity demand, it must be established in terms of "instantaneous" electrical power (kW) required over time (hours) on a daily basis. A load profile for electric power demand would normally include seasonal and scale variations over a year, and the upcoming years.

For a particular time-period of the day, "cumulative" electric energy demand may be calculated as:

$$E = P \times t \qquad (1)$$

where:

E = electric energy (kWh)
P = electric power (kW)
t = time period (hours)

Therefore, required electric energy can be calculated on a daily basis and expressed in terms of kWh/day.

For a particular daily electric energy demand, a load factor can be calculated as:

$$LF = DEE / (MED \times 24 \text{ hours}) \qquad (2)$$

where:

LF = load factor (no units)
DEE = daily electric energy demand (kWh/day)
MED = maximum electric power demand (kW)

In classic electric systems, main criteria for sizing usually include the maximum electric power demand (kW), even if it may only take place once in a while or even if it is expected to take place only several years ahead. However, when dealing with off-grid systems and required storage capacity, energy demand (kWh) plays a critical role for properly sizing a system. Also, load profile plays a critical role considering its potential correlation, or not, in time with a locally available renewable energy source.

B. *Project lifetime and economics*

Project lifetime must be established in order to assess economic feasibility and for comparison purposes among alternative proposals. Usually, project lifetime is considered around 15-25 years.

A key indicator that is used for comparison purposes is the Levelized Cost of Electricity (LCOE) and it can be calculated as follows:

$$LCOE = (CAPEX\text{-}A + OPEX) / E \qquad (3)$$

where:

LCOE = levelized cost of electricity (US$/kWh)
CAPEX-A = capital expenditure (US$/yr)
OPEX = operational expenditures (US$/yr)
E = electricity produced (kWh/yr)

It should be noted that replacement cost of certain components could be incorporated as additional CAPEX that is expected to take place, at a later time, during the project lifetime.

Normally, CAPEX figures are not expressed on a yearly basis but rather on a total cost at the beginning of project lifetime. However, a CAPEX value could be expressed on a yearly basis by:

$$CAPEX\text{-}A = CAPEX \times [i \times (1+i)^n/(1+i)^n-1] \qquad (4)$$

where:

CAPEX = capital expenditure (US$)
i = discount rate (no units)
n = project lifetime (years)

With regard to discount rates, the following relationship applies:

$$NDR = DRD + EIR + DRD \times EIR \qquad (5)$$

NDR = nominal discount rate (no units)
EIR = expected inflation rate (no units)
RDR = real discount rate (no units)

C. *Solar Photovoltaic Generation System*

Electricity produced by solar photovoltaic (PV) systems is directly correlated to local solar radiation availability. It is anticipated that solar radiation will certainly have different values for each month of the year, and it will even be different from day to day. Therefore, it is required to establish a daily solar radiation (W/m^2) availability over time (hour). It should be noted that renewable energy resource availability may or may not necessarily correlate with electric energy demand not even in average values and certainly nor in occurrence over a 24-hr period. Actually, solar energy most likely would only be available at most from 06h00 to 18h00.

Basically, solar PV electricity production will vary during the day as a function of solar radiation. Nominal PV capacity is expressed in terms of kWp which refers to electric power to be produced by the PV modules only if they receive a solar radiation of 1 kW/m^2. An energy storage system is required in order to supply electricity during night time and other intervals of solar resource unavailability. Also, a DC-AC converter would be needed in order to handle the stored energy.

For solar PV systems, CAPEX values are referred to solar PV modules, storage system, and DC-AC converter purchase, including installation costs. OPEX values include only operation and maintenance cost, and it is usually regarded as a low cost, particularly for solar PV modules. Equipment lifetime must be carefully considered in order to properly determine required replacement costs, particularly for the storage system, over project duration.

IV. Results

A simulation process has been conducted, using HOMER Pro, considering two electric load profiles located in Lambayeque, Peru.

A. *Electric Power and Energy Demand*

Two reference electric load profiles for the year 2021 are considered as follows.

TABLE I
REFERENCE ELECTRIC LOAD

Hour	Load1 (kW)	Load2 (kW)
0	2	2
1	2	2
2	2	2
3	2	2
4	2	2
5	3	3
6	5	5
7	7	7
8	8	8
9	8	9
10	8	10
11	8	12
12	8	12
13	8	12
14	8	12
15	8	9
16	9	8
17	10	8
18	12	8
19	12	8
20	12	8
21	12	8
22	9	8
23	5	5

On the basis of above initial data, a daily load of 170 kWh/day would be obtained, along with a peak load of 12 kW, and a load factor of 0.59. However, in order to capture anticipated and more realistic patterns, HOMER Pro introduces Random Variability features such as 10% of day-to-day (size varies but profile shape remains constant) and 20% of timestep (size remains the same but profile shape varies). After considering those Random Variability factors, updated load profile indicates a daily load of 165.44 kWh/day, a peak load of 20.33 kW and a load factor of 0.34, which will be used in this study for simulation purposes. In quantitative terms, both Electric Load 1 and Electric Load 2 involve the same daily energy demand, peak power, and load factor; however, they differ in occurrence over time.

In Fig. 1, it can be seen that Electric Load 1 has more participation during night time. In Peru, for example, electricity prices are higher during peak hours, from 18h00 to 23h00, thus Demand-Side Management strategies are always encouraged.

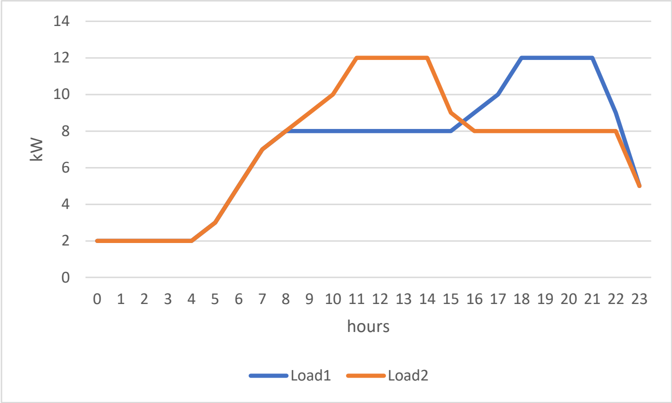

Fig. 1. Reference electric load profiles.

B. *Project lifetime and economics*

Considering local financial context, for this particular case, a nominal discount rate of 12% and an expected inflation rate of 2% are considered. Therefore, a real discount rate of 9.8% would apply.

Project lifetime will be considered as 20 years which is considered as an average reference compared to renewable energy projects in the country.

C. *Solar Photovoltaic System*

In general terms, Peru is considered to have high solar radiation levels but not in all the regions of the country, as indicated in Ref. [08]. As a reference, Lambayeque is located on the northern coastal area of Peru, with a latitude of 6°43.2' South, and a longitude of 79°54.5' West.

Local solar radiation is estimated on the basis of NASA Prediction of Worldwide Energy Resource (POWER) database, using monthly averages for global horizontal radiation over 22-yr period (Jul 1983 – Jun 2005). Table II shows local solar radiation for the present study.

TABLE II
LOCAL SOLAR RADIATION

Month	Clearness Index	Solar Radiation kWh/m2-day
Jan	0.532	5.70
Feb	0.515	5.55
Mar	0.555	5.84
Apr	0.548	5.38
May	0.544	4.89
Jun	0.524	4.47
Jul	0.514	4.48
Aug	0.521	4.91
Sep	0.548	5.59
Oct	0.560	5.95
Nov	0.560	5.98
Dec	0.551	5.86

Source: NASA data built-in HOMER Pro

Local solar radiation in Lambayeque has an average value of 5.38 kWh/m^2-day, with a range from 4.47 kWh/m^2-day (in June) to 5.98 kWh/m^2-day (in November).

It is important to mention that local measurements were conducted only for a few months in order to compare experimental data and NASA information.

For example, Fig. 2 shows a comparison for local solar radiation in April while Fig. 3 shows the comparison for October.

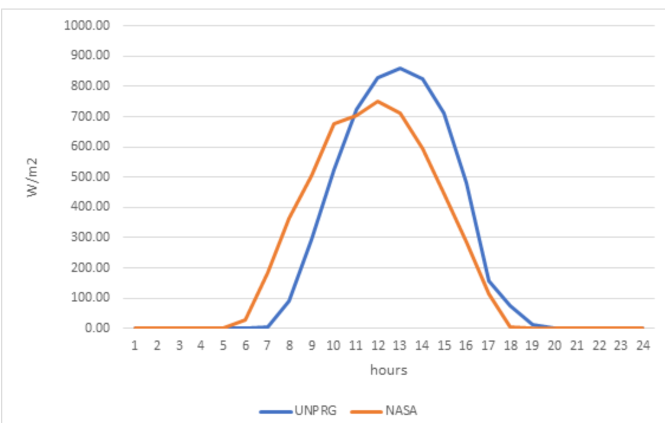

Fig. 2. Daily solar radiation (W/m^2) for April.

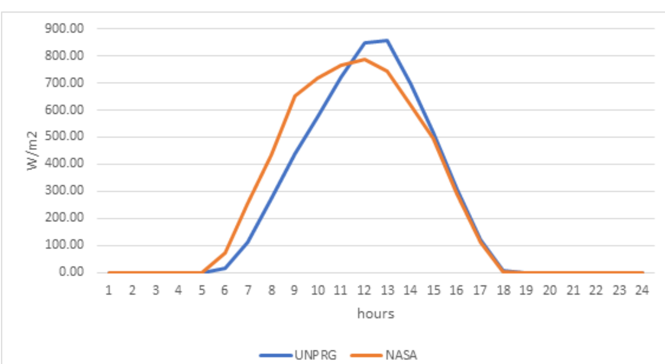

Fig. 3. Daily solar radiation (W/m^2) for October.

A generic PV flat plate is selected using HOMER Pro Library. For a 1-kWp size, CAPEX is estimated as 2,500 US$/kWp while OPEX is considered as 10 US$/yr. Also, a derating factor of 80% for a 20-yr period will be used.

For storage purposes, a generic 1-kWh unit is selected from HOMER Pro Library. CAPEX is estimated as 300 US$/unit while OPEX is considered as 10 US$/yr per unit. Lifetime is considered as 10 years with a throughput of 800 kWh.

Also, a DC-AC converter unit is selected from HOMER Pro Library. CAPEX is estimated as 300 US$/kW while OPEX is considered to be a very low cost.

D. Solar-PV system for Electric Load 1

According to HOMER Pro algorithm, the following optimum solution is obtained for Electric Load 1: 81.5-kW solar PV system, a 657-kWh storage system, and a 44.8-kW DC-AC converter. Fig. 4 shows solar PV generation output, stored energy, and expected electric load for the period Jan-Dec. 2021.

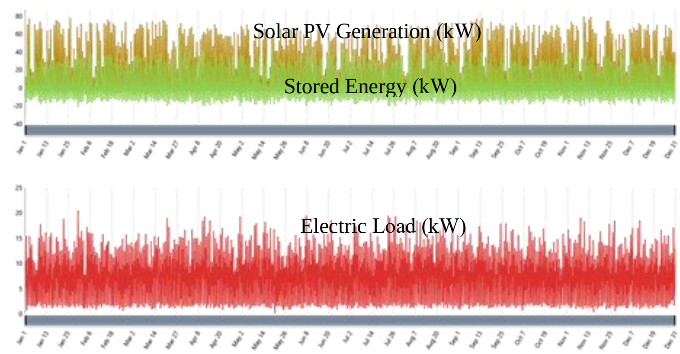

Fig. 4. Solar-PV generation output, stored energy, and electric load.

Total Net Present Cost for the above system is 557,420 US$ and Levelized Cost of Electricity is 1.07 US$/kWh. Total cost for the system includes capital, replacement, operating and maintenance, and salvage for each component: solar PV system, storage system, and DC-AC converter. For the above system CAPEX is 495,073 US$ and OPEX is 16,574 US$/yr.

In the proposed system, 128,222 kWh/yr would be produced, that is 44.5% of excess electricity compared to required electric load.

The solar PV system has a rated capacity of 81.5 kWp, an average output of 14.65 kW and 351 kWh/day. Capacity factor is 17.9% and total production accounts for 128,222 kWh/yr.

The storage system is composed by 657 units of 1-kWh capacity with a total usable capacity of 395 kWh. Autonomy is considered as 57.2 hours while expected life is 10 years. Energy input is 38,673 kWh/yr while energy output is 31,020 kWh/yr. Annual throughput for the energy storage system is 34,681 kWh/yr.

The proposed system includes a 44.8-kW DC-AC converter with an average output of 6.89 kW. Capacity factor is 25.4%, energy input is 63,512 kWh/yr while energy output is 60,336 kWh/yr. In Fig. 5, a basic configuration for the proposed system is shown.

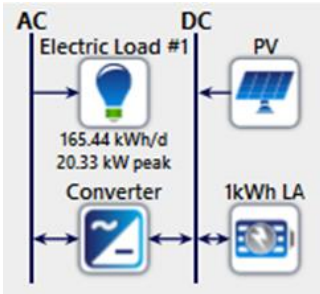

Fig. 5. Basic configuration of a solar-PV generation system

The highest available solar radiation in Lambayeque occurs during November. Fig 6. shows average daily values for solar radiation (kW/m^2) and electric load (kW). It can be noticed that, maximum solar radiation does not correlate with maximum electric load.

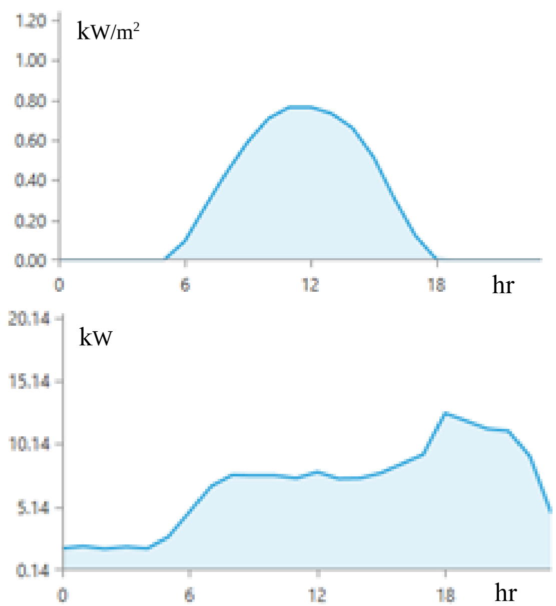

Fig. 6. Daily Solar Radiation (kW/m^2) and Electric Load 1 (kW) in November.

On the other hand, the lowest available solar radiation in Lambayeque occurs during June. Fig 7. shows average daily values for solar radiation (kW/m^2) and electric load (kW). It can be noticed that, maximum solar radiation does not either correlate with maximum electric load.

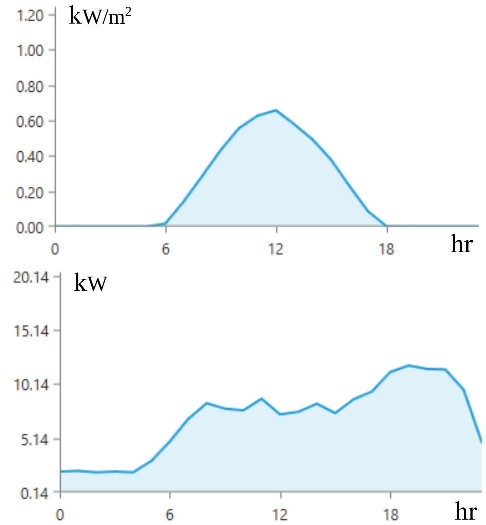

Fig. 7. Daily Solar Radiation (kW/m^2) and Electric Load 2 (kW) in June.

E. Solar-PV system for Electric Load 2

According to HOMER Pro algorithm, the following optimum solution is obtained for Electric Load 2: 103-kW solar PV system, a 443-kWh storage system, and a 29.2-kW DC-AC converter. Fig. 8 shows solar PV generation output, stored energy, and expected electric load for the period Jan-Dec. 2021.

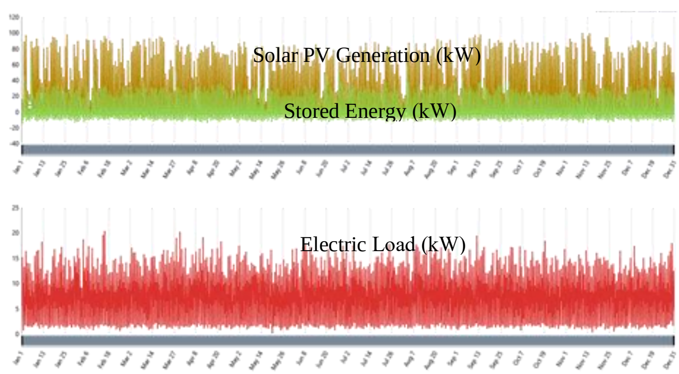

Fig. 8. Solar-PV generation output, stored energy, and electric load.

Total Net Present Cost for the above system is 499,455 US$ and Levelized Cost of Electricity is 0.95 US$/kWh. Total cost for the system includes capital, replacement, operating and maintenance, and salvage for each component: solar PV system, storage system, and DC-AC converter. For the above system CAPEX is 453,068 US$ and OPEX is 11,649 US$/yr.

In the proposed system, 161,815 kWh/yr would be produced, that is 57.1% of excess electricity compared to required electric load.

The solar PV system has a rated capacity of 103 kWp, an average output of 28.5 kW and 443 kWh/day. Capacity factor is 17.9% and total production accounts for 161,815 kWh/yr.

The storage system is composed by 443 units of 1-kWh capacity with a total usable capacity of 266 kWh. Autonomy is considered as 38.6 hours while expected life is 10 years. Energy input is 29,585 kWh/yr while energy output is 23,722 kWh/yr. Annual throughput for the energy storage system is 26,522 kWh/yr.

The proposed system includes a 29.2-kW DC-AC converter with an average output of 6.89 kW. Capacity factor is 23.6%, energy input is 63,514 kWh/yr while energy output is 60,338 kWh/yr. Basic configuration for the proposed system is the same as shown in Fig. 5.

The highest available solar radiation in Lambayeque occurs during November. Fig 9. shows average daily values for solar radiation (kW/m^2) and electric load (kW). It can be noticed that, maximum solar radiation does correlate with maximum electric load.

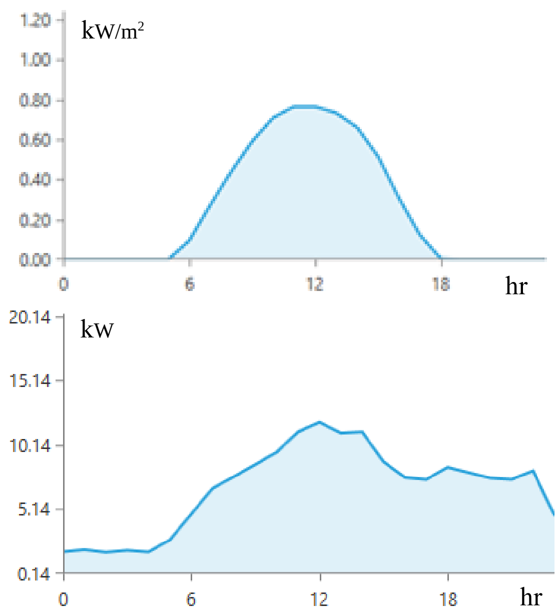

Fig. 9. Daily Solar Radiation (kW/m^2) and Electric Load 2 (kW) in November.

On the other hand, the lowest available solar radiation in Lambayeque occurs during June. Fig 10. shows average daily values for solar radiation (kW/m^2) and electric load (kW). It can be noticed that, maximum solar radiation also correlates with maximum electric load.

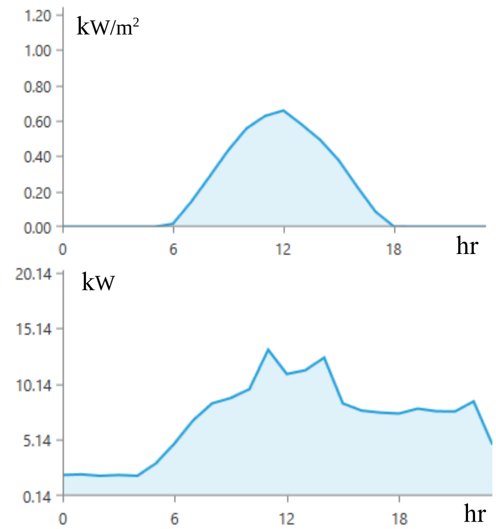

Fig. 10. Daily Solar Radiation (kW/m^2) and Electric Load (kW) in June.

For comparison purposes, the outcoming levelized cost of electricity will be utilized. In order to supply Electric Load 1 using a solar-PV generation system, LCOE is 1.07 US$/kWh, and in order to supply Electric Load 2 using a solar-PV generation system, LCOE is 0.95 US$/kWh. In terms of Net Present Cost, for a solar-PV generation system aimed to supply Electric Load 1, NPC is 557,420 US$, and for a solar-PV generation system aimed to supply Electric Load 2, NPC is 499,455 US$.

Therefore, a solar-PV generation system turns out to be 12.5% more expensive in order to attend Electric Load 2 compared to Electric Load 1, basically due to maximum electric load time of occurrence.

Therefore, it is anticipated that subsequent research work would consider economic benefits associated with Demand-Side Management and End-Use Energy Efficiency.

V. CONCLUSIONS

On the basis of the findings for this study, the following conclusion are outlined.

1. Electricity load is a function of both electric power (kW) and electric energy (kWh) demand. The load profile plays a significant role when considering the potential use of renewable energy sources. In this case, two reference Electric Loads have the same 20.33-kW peak load and load factor of 0.34, but supply electricity cost would be different.
2. Local solar radiation data plays a key role for sizing purposes. Commercial software, like HOMER Pro and others, usually rely on referential databases such NASA and similar ones; however, actual measured data could reveal a different potential for local resource availability. In this case, HOMER Pro built-in database was used for solar radiation estimation due to lack of complete local monthly measured data.

3. In the case of Electric Load 1, its profile indicates that more energy is required during night time. LCOE in this case is 1.07 US$/kWh.
4. In the case of Electric Load 2, its profile indicates that more energy is required during day time. LCOE in this case is 0.95 US$/kWh which is about 12.5% lower compared to the previous case.
5. Discount rates may also play a significant role for cost analysis purposes. Impact of local expected inflation rates would introduce uncertainty with regard to investments in long-term components, usually associated with renewable energy systems. In this study, a conservative estimation of 2% for inflation rate along with a typical nominal discount rate of 12% would lead to a real discount rate of 9.8%.
6. Project lifetime as well as individual component lifetime will also play a significant role in establishing properly replacement costs, particularly energy storage systems.
7. If cost analysis is carried out for on-grid systems, average annual renewable resource availability could be useful; however, for off-grid systems that need to meet a particular electric demand, renewable resource availability over time becomes crucial.
8. Levelized cost of electricity is a suitable approach for cost analysis since it incorporates not only initial costs but also operational and replacement costs during project lifetime.
9. Last but not least, Demand-Side Management and End-Use Energy Efficiency would further contribute to optimize sizing of solar-PV generation systems.

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