Incidence of load profiles in the Levelized Cost of Electricity for a wind power 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 wind power generation system, for a load driven by night-time energy demand, consists of a 168-kW wind power generation system, an 820-kWh storage capacity, and a 90.2-kW DC-AC converter. Also, a proposed wind power generation system, for a load driven by day-time energy demand, consists of the same component configuration.

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 wind speed availability on hourly basis, may not play a significant role for this particular case. Also, gathering local measured data as opposed to using reference databases could further contribute to optimize sizing of wind power generation systems.

Keywords—Wind 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 wind speed 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 is located on the northern coastal region of Peru.

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II. BACKGROUND

According to Ref. [01], this work analyses the techno-economic feasibility of an autonomous hybrid renewable energy system for providing electricity for an academic township in the East District of Sikkim, India. The resources considered for the system were solar energy, wind energy, biogas, syngas and hydrokinetic energy with batteries as back-up. HOMER Pro Microgrid Tool, developed by the National Renewable Energy Laboratory, United States of America has been used as the simulation and assessment tool for modeling performed with hourly data input. Various constraints were implemented to limit the maximum installation capacities of the components considered. All the technical and financial specifications of the components were availed from the local Indian markets. A total of 31 possible combinations of the different resources were analyzed for net present cost, Levelized cost of energy, battery storage, emissions, area requirements and employment potential. The best combination was identified by applying a very widespread multi-criteria decision-making technique named Analytical Hierarchy Process. The Photovoltaic-Wind-Biogas-Syngas-Hydrokinetic-Battery based Hybrid Renewable Energy System was found to be the best combination with a Levelized Cost of Energy of 0.095 $/kWh. Finally, sensitivity analysis was carried out for various parameters to comprehend the behavior of the system for a broader application in the region.

According to Ref. [02], The perpetual dwindling of fossil fuel and its environmental impacts has become a thing of great concern as most countries in the world depend on it for energy generation. The economic development of most of these countries relies on fossil fuel price. Nigeria is one of the countries in the world that solely depends on fossil fuels for electricity generation, and this has greatly affected the growth of its power sector. Hence, there is a need for harnessing renewable energy sources (RES) for electricity generation due to its high availability in abundant quantity in the country. In this study, the viability of developing a standalone hybrid RES system using solar and wind for Giri village (Nigeria) is assessed. The techno-economic and environmental analysis was examined using hybrid optimization model for electric renewable (HOMER) simulation tool by selecting the optimum configuration based on cost of energy (COE), net present cost (NPC), renewable fraction (RF), and greenhouse gas emission (GHG). From the obtained results and sensitivity analysis, the optimal configuration has an NPC of $1.01 m and COE $0.110/kWh, with an operating cost of $4723. The system is environmentally friendly with a renewable fraction of 98.3% and GHG emission of 2889.36 kg/yr.

According to Ref. [03], the primary goal of this study is to determine the minimum cost of energy (COE) for five different global locations – Squamish, Canada; Los Angeles and Golden, USA; and Brisbane and Adelaide, Australia – based on renewable energy systems. We do this by investigating power generation and hydrogen production via renewable energy resources (mainly solar and wind) to produce synthetic fuels by capturing CO2 from the atmosphere. Nine different renewable energy systems are considered based on photovoltaic (PV), wind turbines (WT) and combinations thereof, including battery banks and hydrogen technologies. We used the Hybrid Optimization. Model for Multiple Energy Resources (HOMER Pro) microgrid software to simulate the optimum size of system components and to identify the cost-effective configurations based on particular locations. When considering minimum COE, the results show that integration of PV, WT, a battery bank, an electrolyzer and a hydrogen tank are at 0.50 $/kWh at Golden, Colorado, USA. We also found that without a battery bank, the minimum COE is 0.78 $/kWh at the same location. In this case, the cost increase is due to the capital cost of system components, mainly the hydrogen technologies. The results of this study suggest that hydrogen has economic benefits over batteries for long-term energy storage in off-grid energy systems.

According to Ref. [04], this paper focuses on the techno-economic feasibility of a grid-tied hybrid microgrid system for local inhabitants of Kallar Kahar near Chakwal city of Punjab province in Pakistan and investigates the potential for electricity generation through hybrid wind, photovoltaic and biomass system. The comprehensive resource assessment of wind, biomass and solar energy is carried out for grid integration. Homer Pro software is used to model a hybrid microgrid system. Optimization results and sensitivity analysis is carried out to ensure the robustness and cost-effectiveness of the proposed hybrid microgrid system. The total load has been optimally shared among generated power through wind, photovoltaic and biomass resources and surplus power is supplied to the national grid in case of low local demand of the load. The results of techno- economic feasibility study show that hybrid power system can generate more than 50 MW. The cost of energy based on peak load demand profiles are considered for both residential and commercial sectors. The cost of hybrid system for peak load of 73.6 MW is 180.2 million USD and levelized cost of energy is 0.05744 $/kWh.

According to Ref. [05], Hybrid optimization model for electric renewable (HOMER) Pro is a renewable energy-based system optimization tool developed by National Renewable Energy Laboratory (NREL), USA is used to model HS. It is freely downloadable software. HOMER perform optimization, simulation and sensitivity analysis. This is a general-purpose system design tool that enables power system design either for off-grid or grid-connected application. HOMER sizes up the system specifications such as the load profile, wind resources, solar resources, diesel price, system control parameter, constraint parameter as well as components technical and economics details. HOMER performs numbers of hourly simulation for best possible matching between the load and the supply in order to design an optimal system. Thereafter, it creates feasible system configurations categorized according to cost effectiveness and presents the optimal configuration based on the lowest NPC. HOMER also performs the sensitivity analysis to explore the effect of changes of different factors on the different system configurations. Climatic data [wind speed (WS) and solar irradiation], site load profile, HS component's technical details and costs, system control as well as system constraints serve as input to the software.

According to Ref. [06], Standalone Hybrid Photovoltaic/Wind Energy (PV/WE) systems shall be sized for minimal cost, considering initial capital, continuous operational, and occasional maintenance costs, beside replacement costs over the life of the system. Two of the most utilized sizing techniques are critical month and algorithmic optimization. Critical month technique ensures energy supply without supply and demand (S & D) issues but at the expense of higher cost while algorithmic optimization requires complex mathematical formulations followed by synthesis of appropriate algorithm. This paper proposes a simple mathematical approach to size cost-effective near-optimal hybrid PV/WE system with battery energy storage (BES) and fossil fuel generator (FFG) without complex formulation and algorithm synthesis. Standalone Hybrid PV/WE system with BES and FFG is sized using proposed method and bench marked against a system in Homer Pro Microgrid Analysis Tool. Three systems are sized ranging from few kilo-watts (kW) to mega-watts (MW) in North America, Europe and Southeast Asia to validate proposed method universality.

According to Ref. [07], in this paper, a method for designing hybrid electricity generation systems is presented. It is based on the Modified Electric System Cascade Analysis method. The Power Pinch analysis is used as a guideline for development of an isolated power supply system, which consists of photovoltaic panels, wind turbines and energy storage units. The design procedure uses a simulation model, developed using MATLAB/SIMULINK and applies the developed algorithms for obtaining an optimal design. A validation of the Modified Electric System Cascade Analysis method is performed by comparing the obtained results with those from the Homer Pro software. The procedure takes as inputs hourly wind speed, solar radiation, demands, as well as cost data, for the generation and storage facilities. It is also applied to minimize the loss of power supply probability and to minimize the number of storage units. The algorithm has been demonstrated with a case study on a site in Oujda city, with daily electrical energy demand of 18.7 kWh, resulting in a combination of photovoltaic panels, wind turbine and batteries at minimal cost. The results from the Modified Electric System Cascade Analysis and HOMER Pro show that both tools successfully identified the optimal solution with difference of 0.04% in produced energy, 5.4% in potential excess of electricity and 0.07% in the cost of the energy.

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 wind power 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. Wind Power Generation System

Electricity produced by wind power systems is directly correlated to local wind speed availability. It is anticipated that wind speed 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 wind speed (m/s) 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, wind energy most likely will be available for the 24-hr period but in an intermittent pattern.

Basically, wind electricity production will vary throughout a day as a cubic function of wind speed. Nominal wind power capacity is expressed in terms of kW which refers to electric power to be produced by the wind energy converters only if they receive the nominal wind speed at the rotor center as specified by the manufacturer. An energy storage system is required in order to supply electricity during intervals of low resource availability. Also, a DC-AC converter would be needed in order to handle the stored energy.

For wind energy systems, CAPEX values are referred to wind energy converters, storage system, and DC-AC converter purchase, including installation costs. OPEX values include only operation and maintenance cost. 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.

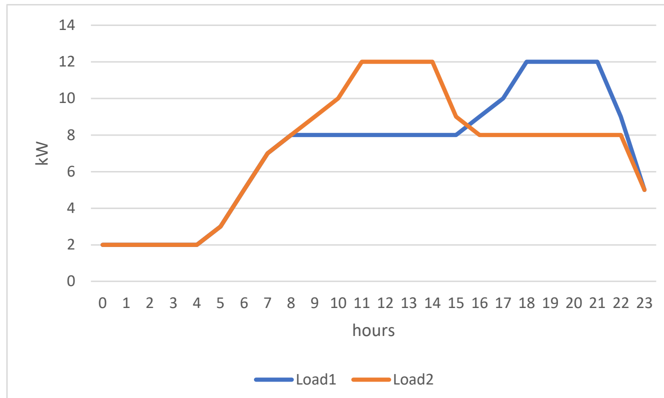

Fig. 1. Reference electric load profiles.

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. *Wind Power Generation System*

In general terms, Peru is considered to have high wind speed 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 wind speed is estimated on the basis of NASA Prediction of Worldwide Energy Resource (POWER) database, using monthly averages for wind speed over a 30-yr period (Jan 1984 – Dec 2013). Table II shows local wind speed for this study.

TABLE II

LOCAL WIND SPEED

Month	Wind Speed (m/s)
Jan	3.78
Feb	3.56
Mar	3.58
Apr	4.05
May	4.42
Jun	4.54
Jul	4.58
Aug	4.58
Sep	4.56
Oct	4.31
Nov	4.12
Dec	3.99

Source: NASA data built-in HOMER Pro

Local wind speed in Lambayeque has an average value of 4.17 m/s, with a range from 3.56 m/s (in February) to 4.58 kWh/m^2-day (in August).

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 wind speed in April while Fig. 3 shows the comparison for October.

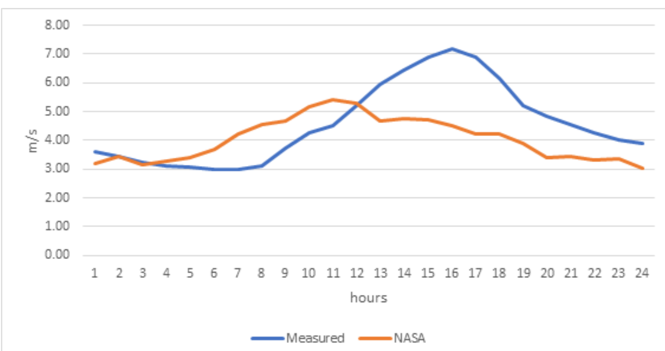

Fig. 2. Wind speed (m/s) for April.

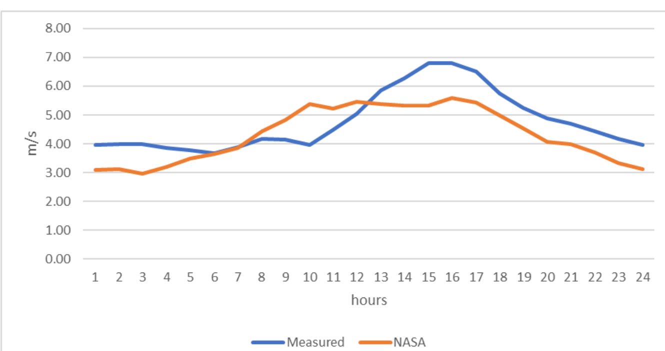

Fig. 3. Wind speed (m/s) for October.

A generic 3-kW wind energy converter is selected using HOMER Pro Library. For a 3-kW unit, CAPEX is estimated as 18,000 US$ while OPEX is considered as 180 US$/yr. Hub height is 17 m and a 20-yr lifetime will be considered.

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. *Wind Power System for Electric Load 1*

According to HOMER Pro algorithm, the following optimum solution is obtained for Electric Load 1: 56 wind energy converters of 3-kW each, an 820-kWh storage system, and a 90.2-kW DC-AC converter. Fig. 4 shows wind power generation output, stored energy, and expected electric load for the period Jan-Dec. 2021.

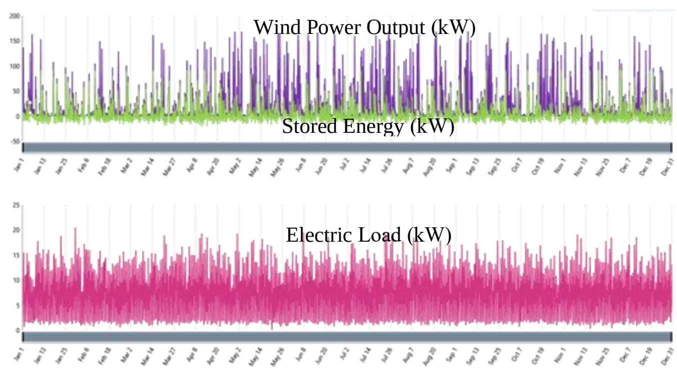

Fig. 4. Wind power generation output, stored energy, and electric load.

Total Net Present Cost for the above system is 1,539,218 US$ and Levelized Cost of Electricity is 3.08 US$/kWh. Total cost for the system includes capital, replacement, operating and maintenance, and salvage for each component: wind turbines, energy storage system, and DC-AC converters. For the above system CAPEX is 1,384,263 US$ and OPEX is 29,918 US$/yr.

In the proposed system, 138,359 kWh/yr would be produced, that is 51.3% of excess electricity compared to required electric load.

The wind power system has a rated capacity of 168 kW, an average output of 15.8 kW and 379 kWh/day. Capacity factor is 9.4% and total production accounts for 138359 kWh/yr.

The storage system is composed by 870 units of 1-kWh capacity with a total usable capacity of 492 kWh. Autonomy is considered as 71.4 hours while expected life is 10 years. Energy input is 33,110 kWh/yr while energy output is 26,734 kWh/yr. Annual throughput for the energy storage system is 29,889 kWh/yr.

The proposed system includes a 90.2-kW DC-AC converter with an average output of 2.9 kW. Capacity factor is 3.21%, energy input is 26,734 kWh/yr while energy output is

25,397 kWh/yr. In Fig. 5, a basic configuration for the proposed system is shown.

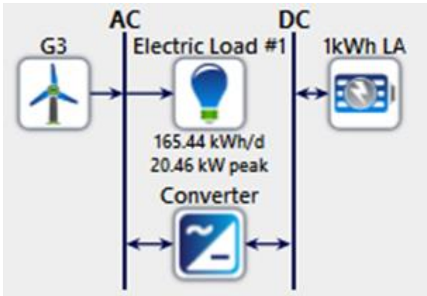

Fig. 5. Basic configuration of a wind power generation system

The highest available wind speed in Lambayeque occurs during August. Fig 6. shows average daily values for wind speed (m/s) and electric load (kW). It can be noticed that, maximum wind speed does not correlate with maximum electric load.

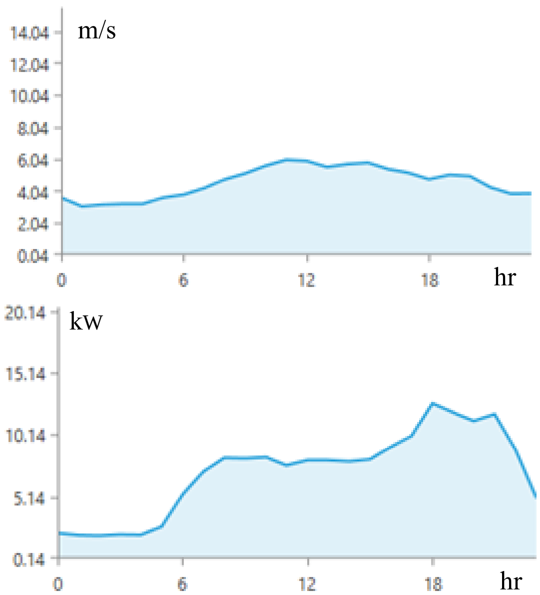

Fig. 6. Wind speed (m/s) and Electric Load 1 (kW) in August.

On the other hand, the lowest available wind speed in Lambayeque occurs during February. Fig 7. shows average values for wind speed (m/s) and electric load (kW). It can be noticed that, maximum wind speed does not either correlate with maximum electric load.

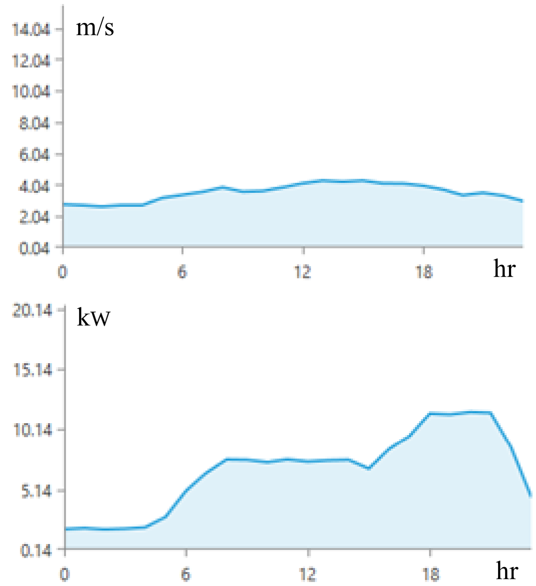

Fig. 7. Daily wind speed (m/s) and Electric Load 2 (kW) in February.

E. *Wind Power System for Electric Load 2*

According to HOMER Pro algorithm, the following optimum solution is obtained for Electric Load 2: 56 wind energy converters of 3-kW each, an 820-kWh storage system, and a 90.2-kW DC-AC converter. Fig. 8 shows wind power generation output, stored energy, and expected electric load for the period Jan-Dec. 2021.

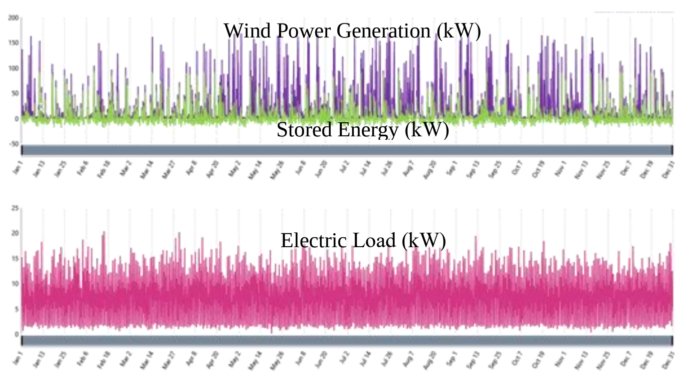

Fig. 8. Wind power generation output, stored energy, and electric load.

Total Net Present Cost for the above system is 1,539,218 US$ and Levelized Cost of Electricity is 3.07 US$/kWh. Total cost for the system includes capital, replacement, operating and maintenance, and salvage for each component: wind energy converters, energy storage system, and DC-AC converters. For the above system CAPEX is 1,384,263 US$ and OPEX is 29,918 US$/yr.

In the proposed system, 138,359 kWh/yr would be produced, that is 51.4 of excess electricity compared to required electric load.

The wind power system has a rated capacity of 168 kW, an average output of 15.8 kW and 379 kWh/day. Capacity factor is 9.40% and total production accounts for 138,359 kWh/yr.

The storage system is composed by 820 units of 1-kWh capacity with a total usable capacity of 266 kWh. Autonomy is considered as 71.4 hours while expected life is 10 years. Energy input is 32,195 kWh/yr while energy output is 26,000 kWh/yr. Annual throughput for the energy storage system is 29,069 kWh/yr.

The proposed system includes a 90.2-kW DC-AC converter with an average output of 2.82 kW. Capacity factor is 3.136%, energy input is 26,000 kWh/yr while energy output is 24,700 kWh/yr. Basic configuration for the proposed system is the same as shown in Fig. 5.

The highest available wind speed in Lambayeque occurs during August. Fig 9. shows average daily values for wind speed (m/s) and electric load (kW). It can be noticed that, maximum wind speed does correlate with maximum electric load.

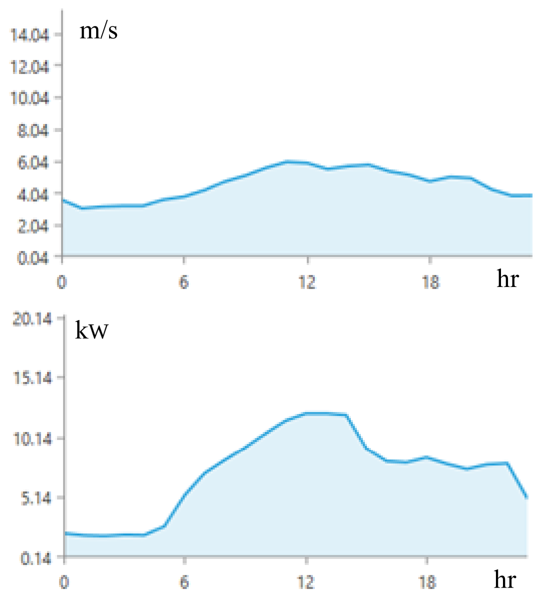

Fig. 9. Wind speed (m/s) and Electric Load 2 (kW) in August.

On the other hand, the lowest available wind speed in Lambayeque occurs during February. Fig 10. shows average daily values for wind speed (m/s) and electric load (kW). It can be noticed that, maximum wind speed also does correlate with maximum electric load.

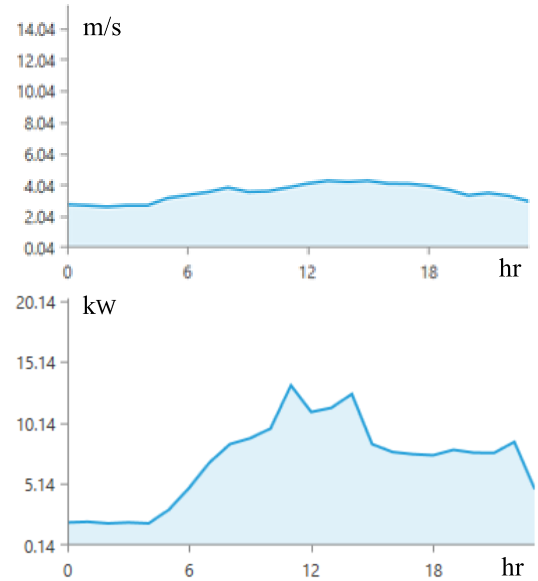

Fig. 10. Wind speed (m/s) and Electric Load (kW) in February.

For comparison purposes, the outcoming levelized cost of electricity will be utilized. In order to supply Electric Load 1 using a wind power generation system, LCOE is 3.08 US$/kWh, and in order to supply Electric Load 2 using a wind power generation system, LCOE is 3.07 US$/kWh. In terms of Net Present Cost, for a wind power generation system aimed to supply Electric Load 1, NPC is 1,539,218 US$, and for a wind power generation system aimed to supply Electric Load 2, NPC is 1,539,218.

Therefore, in this case, a wind power generation system turns out to be almost equally expensive in order to attend Electric Load 2 compared to Electric Load 1, basically due to low wind speed availability despite the different load profiles.

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 could play 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 with different profile over time. However, cost of electricity generation would remain the same.
2. Wind speed data plays a key role for sizing purposes, particularly because power output is a cubic function of wind speed. 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 wind speed 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 3.08 US$/kWh. In the case of Electric Load 2, its profile indicates that more energy is required during day time. LCOE in this case is 3.07 US$/kWh which is about the same cost compared to the previous case.
4. 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%.
5. Project lifetime as well as individual component lifetime will also play a significant role in establishing properly replacement costs, particularly energy storage systems.
6. 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.
7. 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.
8. Last but not least, gathering local measured data as opposed to using reference databases could further contribute to optimize sizing of wind power generation systems

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