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Techno-Economic-Environmental Assessment of an Isolated Rural Micro-Grid from a Mid-Career Repowering Perspective

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Abstract: Pakistan is an energy deficient country with depleting energy reserves and increasing energy demand. Due to excessive population growth, the domestic and commercial energy sectors are experiencing rising demand. To meet the requisite demand, renewables are favored rather than conventional-counterparts. In this study, we model hybrid power systems using solar, wind and biomass resources for electrifying remote areas. The four locations are chosen for the study around a developing country, Pakistan, where each site is designed according to an isolated microgrid with maximum indigenous resources potential as per the requisite demands. A survey is conducted for the load demand and biomass availability. Optimization is conducted across objectives of minimum levelized cost of the generated energy, least the net present cost and lesser payback period. The optimal results were achieved in-terms of required objectives across southern sites as compared to northern counterparts. The cost of generated energy is comparable to grid electricity and ensures 24 h power supply without cut off and load shedding to the un-electrified rural area.-The hybrid power system has a low carbon footprint across emissions due to the use of renewable resources. All the estimated load of rural communities is met with the available resources and mid-career impact has also been conducted across 10 years of the project life to fulfill the increasing load demand of the communities after installation. The results are validated via comparative analysis and show the effectiveness of the proposed study.

Keywords: hybrid renewable energy system; micro-grid; net present cost; payback period; rural electrification

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1. Introduction

Electricity access is essential in developing countries for industrial development and reducing poverty [1,2]. Although 99 percent of North Africans have access to electricity, 0.6 billion natives in sub-Saharan Africa still do not have electricity [3]. Likewise, 45 percent of the population of Nigeria has proper access to grid electricity [4]. This is not acceptable for the largest oil producing country (Africa) with fossil fuels as the most dominant energy resource for producing electricity. Despite this, the majority of the population with access to electricity frequently faces blackouts causing huge losses in the business economy and critical services. Inappropriate generation capacity, and old transmission and distribution systems with no or bad maintenance systems have been considered responsible [5]. Due to these issues, diesel generators are sometimes used to fulfill the energy demand quickly and rapidly, but they have harmful emissions making them an unfavorable approach due to environmental concerns. However, higher operational cost, limited oil reserves, the price inflation of petroleum and, most concerningly, environmental degradation caused by greenhouse gas emissions are driving the need for sustainable solutions. The current trend of central and back-up power production is shifting towards renewables and out of these fossil fuels, and solar and wind are the most favorable alternatives for energy production in areas with a high proportion of these resources. Additionally, biomass and hydro resources are also favorable in some regions with excess availability of these resources [6].

Over the last few decades, climatic catastrophe due to the excessive discharge of GHG emissions derived from the use of fossil fuels is the most highlighted concern globally. Developed nations have committed to reducing these harmful emissions through nationally determined contributions (NDC) as a rapid response and limiting the rise of the earth's temperature below 2 °C since 1990 [7]. Electrical energy is essential for the economic development of a country, and it adds a positive addition to the gross domestic product (GDP) [8]. In this modern world, electricity is a basic human need to power human activity, from a pocket size mobile phone to spaceships, which all need electrical energy for their routine operation. Moreover, for remote locations, it reduces poverty by providing employment opportunities and improving the human-development index (HDI). The World Bank reported that almost 11.3% of the world population had no electricity until 2017 [9].

Approximately 0.84 billion people lack access to electricity globally [10]. The energy transition towards cleaner energy generations has the potential to drive broader socioeconomic growth [11]. This transition requires a broader range of policies to encourage the development of the decarbonization of rural communities. It is of utmost necessity to develop renewable resources options to resolve the issue of rural electrification problems, and these alternative approaches would aid in energy decarbonization, along with economic, environmental and social development [12]. Studies revealed that growing energy demand, environmental concerns and limited fossil reserves lead towards alternative resources for fulfilling future energy demand. To meet this demand, distributed energy generation (DG) is widely used around the world based on solar, wind, hydro and biomass resources [13]. The application of DG based on renewable resources would ultimately lead towards zero carbon emissions, which is the goal of many countries.

Electric generation is being conducted in a centralized mode globally in which power is produced at the generating stations located far away from the end users, which involves high transmission and distribution costs, along with the losses associated with the long distant transmission lines that normally cause 7–10% of voltage losses. To feed the required electric load, more generation is required due to these losses that add to the overall cost of centralized power generation [12]. Contrary to the traditional regime, distributed power generation is generated near the consumer and supplied directly without any transmission network. DG can be termed as distributed-power, distributed-generation, integrated DG, hybrid DG, and decentralized energy-system [13,14].

Drivers that are leading the transition from centralized to decentralized energy generation include the advent of sustainable development goals set by the United Nations Development Program (UNDP), aiming to mitigate climate catastrophe caused by the excessive use of fossil fuels to reduce the harmful emissions by increasing the importance of using and adopting energy efficient measures and production from renewables that would ultimately reduce energy imports and improve energy security at the national level, and fulfill the rising energy demand of the developed and developing nations [12]. The North-American Electric Reliability Corporation (NERC) states that, "A distributed energy resource is any resource on the distribution system that produces electricity and is not otherwise included in the formal NERC definition of the bulk electric system".

Micro-grids are considered a localized electric-power system containing distributed generation (DG), electrical loads and storage devices. The CIGRE C 6.22 working group micro-grid evolution roadmap states a micro-grid as an "electricity distribution system containing electric loads and distributed energy resources (DER) incorporates DGs, storage devices or controllable loads, which can be operated in a controlled coordinated way either in a grid-connected mode or islanded mode". Further, the US Department of Energy defines the micro grid as, "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A micro-grid can connect and disconnect from the grid to enable it to operate both in on-grid or off-grid mode" [15].

Traditionally, rural communities are heavily dependent on diesel power generation for their energy needs, which is responsible for a high rate of harmful emissions [15]. DG based on renewables is replacing these conventional fossil fuel-based power generating units [16]. It is critical to design optimal DER economically without endangering the reliable electric supply to the locals [17]. Maximum renewables penetration [18,19], the lowest installation cost [20,21] and operational cost [22,23], maximum reliability of the electric power supply [24] and the lowest emissions from the system [25–29] are the necessary objectives to plan and size a DES for rural areas. Furthermore, several social benefits such as job creation and women empowerment must be considered as secondary objectives while planning DESs for rural communities [30,31].

Pakistan has been facing an energy deficit in generation to meet growing demand for a long time. Most of the country's energy is being generated through fossil fuels [26]. As a result, not only are energy reserves being depleted due to the excessive usage but a huge amount of greenhouse gases is emitted into the environment, which is contributing to global warming [27]. Global warming is the foremost environmental concern around the globe at the current time. Electrical energy has become a necessity worldwide but it is not available to all the communities across the world [28]. Around one and a half billion people in the world have no access to electricity and approximately one billion have partial or little access to electricity with frequent blackouts [31,32]. The isolated micro-grid is one of the means to achieve carbon neutrality considering the indigenous renewable resource potential, supported by multi-dimensional analysis. Moreover, the provision of midcareer repowering analysis must be conducted across a planning horizon for the sustainable running of the system.

This situation is more critical at remote locations in the developing world where around 95 percent of communities located in these areas lack proper grid electricity [33]. The residents of these remote locations are facing energy poverty, which can be expressed as the "absence of energy access to the present services". The lack of modern energy in the emerging world is the utmost prominent hurdle to a nation's prosperity and development, as it critically delays financial growth and progress [34]. Pakistan lies in the south of Asia, and it is the best example among developing countries making an effort to resolve the energy shortage. Around two-thirds of the nation's population is living in rural regions [35]. From the rural inhabitants, a substantial fraction of about 97 percent of these communities face a high proportion of energy unavailability, which takes place in the form of routine power cuts that produce harmful impacts on the welfare of human life, growth and progress. Due to this unavailability and partial availability of electricity to these areas' backup generators, storage elements with PV modules, kerosene oil, biomass and candles are being used in these remote areas. These sources are not a permanent solution to these remote locations and they are not feasible technically, economically, or environmentally. Therefore, a microgrid standalone hybrid system with a high penetration of renewable resources would be a better approach to the rural areas, which require high transmission lines costs due to the relatively high distance from the generating and distributing stations. In rural areas, the population is dispersed with a low load factor, low population density and improper infrastructure [36].

In hybrid renewable energy systems (HRES), various strategies are being employed for energy conversion including: photovoltaics (PV), micro-hydro, wind-turbine, biomass, etc. Furthermore, grid-scale energy storage technologies are improving rapidly and can be upgraded through the integration of RES powered distributed generation (DG) in a power system [37]. To provide a reliable and secure supply of electrical energy to these remote locations, we need to do either a grid extension or make a standalone microgrid type system with high integration of renewable energy resources. Grid extension is not feasible due to the limited energy reserves and long distances from national grids. Therefore, the designing of hybrid power systems for rural locations would provide a more beneficial, self-sustaining and viable source of energy. Other than increasing the country's growth towards energy generation, toxic emissions to the atmosphere by the use of conventional resources would be minimized, which would ultimately help in fulfilling the targets set in the Paris Agreement in 2015 and Conference of Parties (COP), such as COP26 and COP27 in 2021 and 2022, respectively, to save the environment from climatic catastrophe and global warming. These targets aim to keep the indigenous measures of the earth's temperature at 2 °C, or at least 1.5 °C lower than in pre-industrial times, with global emissions reduced to half by 2030 and zero-carbon emissions achieved by the end of 2050 [38].

Rural electrification through a standalone hybrid scheme provides the locals with environmentally comprehensive protection, and it would decrease energy poverty at the same time. This scheme would help a country meet its commitment to the Kyoto Protocol, e.g., Pakistan signed an agreement in December 1997 (ratified January 2005) stating that it would decrease harmful emissions [39], which ultimately would assist our development by promoting a greener image and accelerating economic progress and growth. A safe electricity supply benefits the public by providing schooling to the children, health facilities and small home-based jobs to women like sewing and stitching.

Due to the increasingly extreme temperature variations, transitioning towards green energy resources is a pressing need. Solar, wind and biomass are considered clean energy resources with the least CO_2 emissions. Energy generation from biomass is the best approach to using biomass waste that not only produces useful energy but also reduces community waste, which otherwise becomes dumped waste if not used for energy generation. Solar and wind reduces the dependence on fossil fuels, which are imported. At the same time, these are an optimal solution for remote areas where grid extension is highly expensive and unable to reach energy consumers [40].

In contrast to approaches to electricity production using fossil fuels, wind energy produces electrical energy from freely available natural resources. Wind energy is an indigenous energy source that does not need to be extracted or even moved at high and wide-ranging power costs [41]. Most regions in Pakistan lie in the earth's sunny belt. Daily sunshine hours range from 6 to 8.5 h per day. This solar radiation contains a lot of energy. In Pakistan, the average solar radiation received annually on the surface is from 4.7 to 6.2 kWh/m^2, while the total average radiation received is 5.45 kWh/m^2 [42]. Here, we can see even the lower end of radiation is much greater than radiation in the European countries. The officially disclosed wind energy potential for Balochistan and Sindh is around 50,000 megawatts, and for the Punjab region around 10,000 megawatts [43].

In this paper in which we aim to bridge these limitations, the highlights of the proposed work are shown below:

1. Indigenous resource assessments
2. Isolated microgrid design and optimization for rural areas
3. Multi-dimensional (techno-economic-environmental) analysis
4. Small-scale measures for a certain percentage of carbon neutrality
5. Mid-career repowering across future requirements
6. Cases and scenarios considering variables like seasonal variations

The paper s organized as follows. The methodology is presented in Section 2. The software setup and parameters are shown in Section 3. In Section 4, the hybrid system is designed as per various system components. Section 5 presents the results and discussion. The paper is concluded in Section 6.

2. Methodology

The discussion above clearly shows that remote areas in the country have not been given much importance till now. Now the foremost priority is the selection of appropriate technology and modeling of renewables based on the microgrid to electrify deprived communities. Across the world over the last few decades, renewable technologies have received a lot of attention as a source of electricity. With Pakistan's exceptional renewable energy potential in the form solar, wind and biomass, it is time to promote renewable energy technologies, which is a long-term alternative to the conventional grid that can bring thousands of people out of the dark while developing a strong and stable economy.

The selected areas are non-electrified or partially electrified where villagers have no or improper access to grid electricity and each of the selected remote regions is located more than 20 km from the national grids. The load profile of the proposed areas was calculated through a real time survey. Around 20 houses in the Punjab region and Sindh region and 10 houses from the KPK and Baluchistan communities were visited, and the selected houses provided a true representation for estimating the load of whole communities. Solar and wind data were gathered from the National Renewable Energy Laboratory (NREL) database and biomass data were estimated during the survey [42]. Figure 1 shows the steps involved in this study. In this study, a renewable resources-based hybrid power system was designed for each location and the results compared with a diesel generator and grid extension break-even limit, while keeping in view the topography of the rural area.

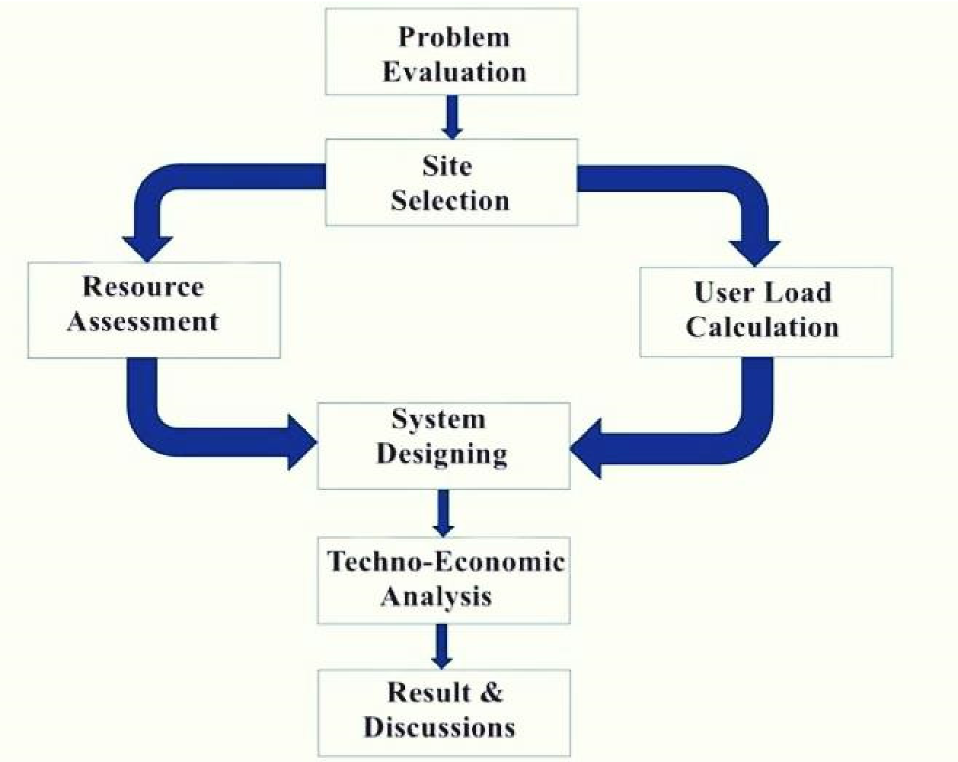


Figure 1. Flow chart of this study.

2.1. Site Selection

The main theme of the research is to electrify the rural communities still deprived of electricity. It was observed during site surveys that at the selected sites most of the houses have cattle, which is a better source of biomass and income for the locals. Figures 2–5 show the Google Earth view of the four proposed remote areas located in different provinces of Pakistan.

Figure 2. Google Earth view of Chak 68-DB.

Figure 3. Google Earth view of Shahi Bala KPK

Figure 4. Google Earth view of Mastung, Balaochistan

Figure 5. Google Earth view of Dilmurad Mahar, Sindh

2.2. Load Calculation

After site selection, user load estimation worse performed based on the demand of locals. All types of houses having low, medium and high energy demand are included. The whole community load is then calculated as an average load estimated from the fixed number of houses that represented the whole community load demand. Each community includes at least one mosque, small medical health facility and a primary school for kids. All electrical loads are estimated in terms of summer and winter loads. The summer load is taken from February till September and winter load considered from October till January. The winter load excluded the fans load.

Initially, the load was calculated for each appliance for an individual house. Then, we simply added all appliance loads for an individual house. Then, we calculated summer and winter loads using Equations (2) and (3), respectively. Then, the yearly load for each house is calculated using eq. 4. Then, we took the average of all houses' yearly loads using Equation (5) and estimated the per house average load using Equation (6). Finally, the entire load is calculated using Equation (7). Tables 1–4 show the load data estimations for all the rural communities.

The mathematical formulas derived for load estimation are given below

$$\text{Load (Wh)} = \text{No. of appliances} \times \text{Wattage} \times \text{No. of intended hours of use} \quad (1)$$

$$\text{Summer load (kWh/day)} = \text{Sum of loads of all appliances} \quad (2)$$

$$\text{Winter load (kWh/day)} = \text{Summer load} - \text{Fans load} \quad (3)$$

$$\text{Total yearly kWh/day} = (\text{Winter load} + \text{Summer load})/2 \quad (4)$$

$$\text{Average of 11 houses} = (\text{sum of all houses' individual house loads})/\text{no. of houses} \quad (5)$$

$$\text{Per house load} = (\text{average of 11 houses})/11 \quad (6)$$

$$\text{Community load} = \text{Per house load x total no. of houses in the community} \quad (7)$$

Table 1. Load data Calculations for Chak 68 DB Punjab.

No. of Houses	Lights (Wh)	Fans (Wh)	TV (Wh)	Refrigerator (Wh)	Water Pump (Wh)	Phone Charger (Wh)	Load in Summer (kWh/day)	Load in Winter (kWh/day)
1	4 × 20 × 14 = 1120	2 × 75 × 12 = 1800	1 × 120 × 3 = 360	NA	1 × 1200 × 0.5 = 600	1 × 8 × 2 = 16	3.896	2.096
2	3 × 20 × 12 = 720	2 × 75 × 11 = 1650	NA	NA	1 × 1200 × 0.5 = 600	1 × 8 × 2 = 16	2.986	1.336
3	4 × 20 × 10 = 800	2 × 75 × 12 = 1800	1 × 120 × 2 = 240	NA	1 × 1200 × 0.5 = 600	1 × 8 × 2 = 16	3.456	1.656
4	4 × 20 × 12 = 960	2 × 75 × 10 = 1500	1 × 120 × 2 = 240	NA	1 × 1200 × 0.5 = 600	1 × 8 × 2 = 16	3.316	1.816
5	5 × 20 × 13 = 1300	2 × 75 × 12 = 1800	1 × 120 × 3 = 360	NA	1 × 1200 × 0.25 = 300	1 × 8 × 2 = 16	3.776	1.976
6	4 × 20 × 10 = 800	2 × 75 × 8 = 1200	1 × 120 × 2 = 240	NA	1 × 1200 × 0.25 = 300	1 × 8 × 2 = 16	2.556	1.356
7	4 × 20 × 8 = 640	2 × 75 × 10 = 1500	1 × 120 × 3 = 360	1 × 240 × 16 = 3840	1 × 1200 × 0.25 = 300	1 × 8 × 2 = 16	6.676	5.176
8	4 × 20 × 9= 720	2 × 75 × 8 = 1200	1 × 120 × 3 = 360	1 × 240 × 14 = 3360	1 × 1200 × 0.25 = 300	2 × 8 × 2 = 32	5.972	4.772
9	8 × 20 × 8 = 1280	4 × 75 × 8 = 2400	1 × 120 × 3= 360	1 × 240 × 16 = 3840	1 × 1200 × 0.5 = 600	2 × 8 × 2 = 32	8.512	6.112
10	14 × 20 × 5 = 1400	10 × 75 × 4 = 3000	NA	NA	1 × 1200 × 0.6 = 720	NA	5.0	2.0
Load in Summer					Load in Winter			
• Total watt-hours/day = 46.146 kWh • Watt-hours/house = 46.146/10 = 4.615 kWh • Total kilowatt-hours for 150 houses = 200 × 4.615 = 923 kWh/day					• Total watt-hours/day = 28.296 kWh • Watt-hours/house = 28.296/10 = 2.83 kWh • Total kilowatt-hours for 150 houses = 2.83 × 200 = 566 kWh/day			
For the community of 150 houses, annual mean load = (923 + 566)/2 = 1489 kWh/day								

Table 2. Load data Calculations for Dilmurad Mahar Sindh.

No. of Houses	Lights (Wh)	Fans (Wh)	TV (Wh)	Refrigerator (Wh)	Water Pump (Wh)	Phone Charger (Wh)	Load in Summer (kWh/day)	Load in Winter (kWh/day)
1	4 × 15 × 9 = 540	2 × 80 × 12 = 1920	1 × 80 × 4 = 320	1 × 250 × 12 = 3000	1 × 1200 × 0.5 = 600	1 × 8 × 2 = 16	3.896	2.096
2	4 × 20 × 12 = 960	2 × 75 × 11 = 1650	NA	NA	1 × 1200 × 0.75 = 900	1 × 8 × 2 = 16	3.526	1.876
3	4 × 20 × 10 = 800	2 × 75 × 12 = 1800	1 × 120 × 2 = 240	NA	1 × 1200 × 0.5 = 600	1 × 8 × 2 = 16	3.456	1.656
4	4 × 20 × 12 = 960	2 × 75 × 10 = 1500	1 × 120 × 2 = 240	NA	1 × 1200 × 0.5 = 600	1 × 8 × 2 = 16	3.316	1.816
5	6 × 20 × 13 = 1560	2 × 75 × 12 = 1800	1 × 120 × 3 = 360	NA	1 × 1200 × 0.25 = 300	1 × 8 × 2 = 16	4.036	2.236
6	4 × 20 × 10 = 800	2 × 75 × 8 = 1200	1 × 120 × 2 = 240	NA	1 × 1200 × 0.25 = 300	1 × 8 × 2 = 16	2.556	1.356
7	4 × 20 × 8 = 640	2 × 75 × 10 = 1500	1 × 120 × 3 = 360	1 × 240 × 16 = 3840	1 × 1200 × 0.25 = 300	1 × 8 × 2 = 16	6.676	5.176
8	4 × 20 × 9 = 720	2 × 75 × 8 = 1200	1 × 120 × 3 = 360	1 × 240 × 14 = 3360	1 × 1200 × 0.25 = 300	2 × 8 × 2 = 32	5.972	4.772
9	8 × 20 × 8 = 1280	4 × 75 × 8 = 2400	1 × 120 × 3 = 360	1 × 240 × 16 = 3840	1 × 1200 × 0.5 = 600	2 × 8 × 2 = 32	8.512	6.112

10	16 × 20 × 5 = 1600	10 × 75 × 4 = 3000	NA	NA	1 × 1200 × 0.75 = 900	NA	5.5	2.5

Load in Summer	Load in Winter
• Total watt-hours/day for = 47.446 kWh • Watt-hours/house = 47.446/10 = 4.745 kWh • Total kilowatt-hours for 150 houses = 150 × 4.745 = 711.69 kWh/day	• Total watt-hours/day = 29.596 kWh • Watt-hours/house = 29.596/10 = 2.96 kWh • Total kilowatt-hours for 150 houses = 2.96 × 150 = 444 kWh/day
For the community of 150 houses, annually mean load = (711.69 + 444)/2 = 577.845 kWh/day	

Table 3. Load data Calculations Shahi Bala KPK.

No. of Houses	Lights (Wh)	Fans (Wh)	TV (Wh)	Refrigerator (Wh)	Water Pump (Wh)	Phone Charger (Wh)	Load in Summer (kWh/day)	Load in Winter (kWh/day)
1	5 × 20 × 8 = 800	3 × 75 × 8 = 1800	1 × 120 × 3 = 360	NA	1 × 1200 × 0.5 = 600	1 × 8 × 2 = 16	3.576	1.776
2	4 × 20 × 8 = 640	2 × 75 × 10 = 1500	1 × 120 × 3 = 360	1 × 240 × 16 = 3840	1 × 1200 × 0.25 = 300	1 × 8 × 2 = 16	6.676	5.176
3	4 × 20 × 9 = 720	2 × 75 × 8 = 1200	1 × 120 × 3 = 360	1 × 240 × 14 = 3360	1 × 1200 × 0.25 = 300	2 × 8 × 2 = 32	5.972	4.772
4	8 × 20 × 8 = 1280	4 × 75 × 8 = 2400	1 × 120 × 3 = 360	1 × 240 × 16 = 3840	1 × 1200 × 0.5 = 600	2 × 8 × 2 = 32	8.512	6.112
5	15 × 20 × 5 = 1500	10 × 75 × 4 = 3000	NA	NA	1 × 1200 × 0.75 = 900	NA	5.4	2.4

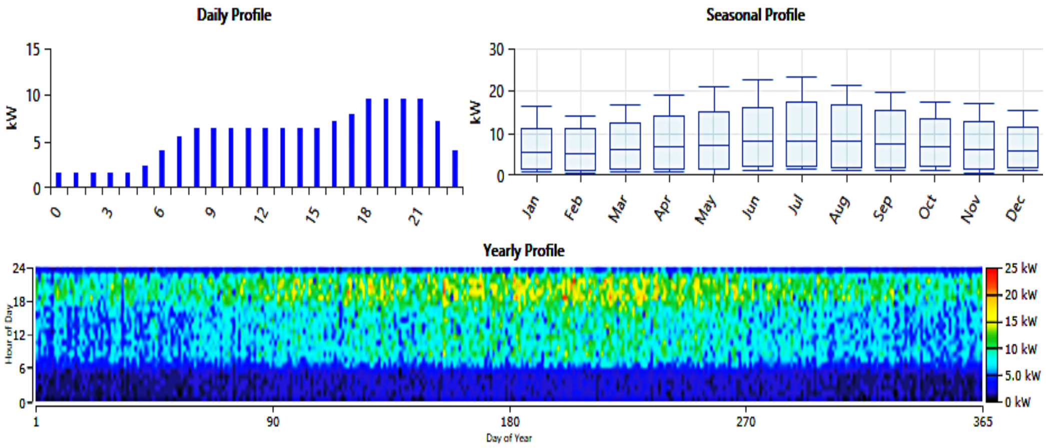
Load in Summer	Load in Winter
• Total watt-hours/day = 30.136 kWh • Watt-hours/house = 30.136/5 = 6.027 kWh • Total kilowatt-hours for 200 houses = 200 × 6.027 = 1205.44 kWh/day	• Total watt-hours/day = 20.236 kWh • Watt-hours/house = 20.236/5 = 4.05 kWh • Total kilowatt-hours for 200 houses = 4.05 × 200 = 810 kWh/day
For the community of 200 houses, annual mean load = (1205.44 + 810)/2 = 1007.72 kWh/day	

Table 4. Load data Calculations for Mastung Balochistan.

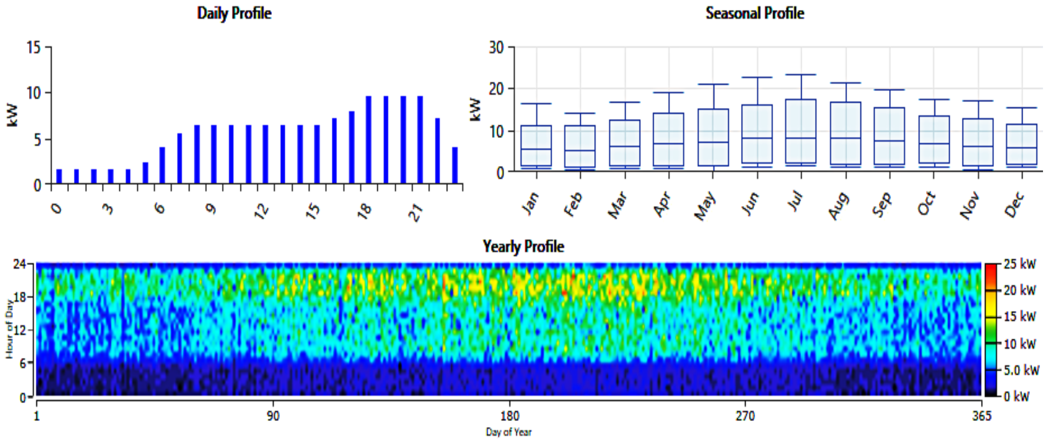
No. of Houses	Lights (Wh)	Fans (Wh)	TV (Wh)	Refrigerator (Wh)	Water Pump (Wh)	Phone Charger (Wh)	Load in Summer (kWh/day)	Load in Winter (kWh/day)
1	4 × 20 × 14 = 1120	2 × 75 × 12 = 1800	1 × 120 × 3= 360	NA	1 × 1200 × 0.5 = 600	1 × 8 × 2 = 16	3.896	2.096
2	4 × 20 × 12 = 960	4 × 75 × 11 = 3300	NA	NA	1 × 1200 × 0.5 = 600	1 × 8 × 2 = 16	4.876	1.576
3	4 × 20 × 10 = 800	2 × 75 × 12 = 1800	1 × 120 × 2 = 240	NA	1 × 1200 × 0.5 = 600	1 × 8 × 2 = 16	3.456	1.656
4	4 × 20 × 10 = 800	3 × 75 × 10 = 2250	1 × 120 × 2 = 240	NA	1 × 1200 × 0.5 = 600	1 × 8 × 2 = 16	3.906	1.656
5	25 × 20 × 13 = 6500	10 × 75 × 12 = 9000	NA	NA	1 × 1200 × 1 = 1200	NA	16.70	7.70

Load in Summer	Load in Winter
• Total watt-hours/day = 32.834 kWh • Watt-hours/house = 32.834/5 = 6.567 kWh • Total kilowatt-hours for 250 houses = 250 × 6.576 = 1641.75 kWh/day	• Total watt-hours/day = 14.684 kWh • Watt-hours/house = 14.684/5 = 2.937 kWh • Total kilowatt-hours for 250 houses = 2.937 × 250 = 734.25 kWh/day
For the community of 150 houses, annually mean load= (1641.75 + 734.25)/2 = 2376 kWh/day	

Figure 6a–d shows daily, seasonal and yearly load profiles for the entire day for all proposed remote locations.



(a)



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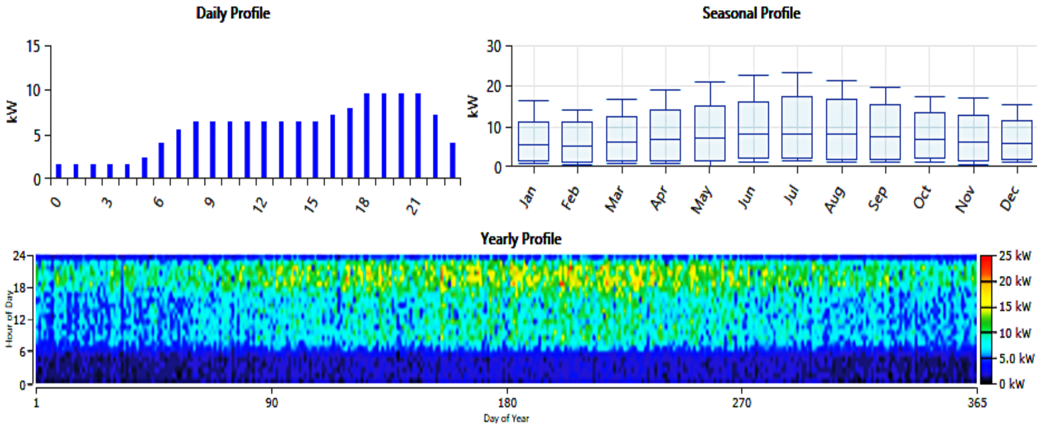

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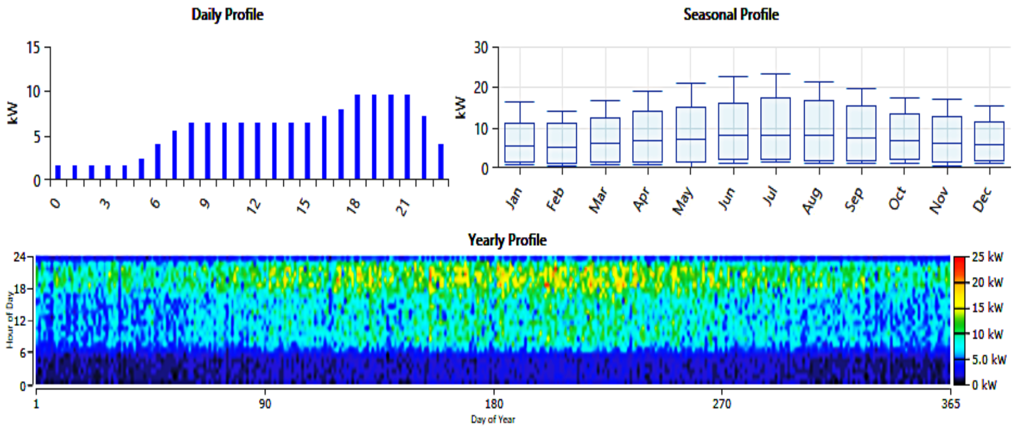


(**d**)

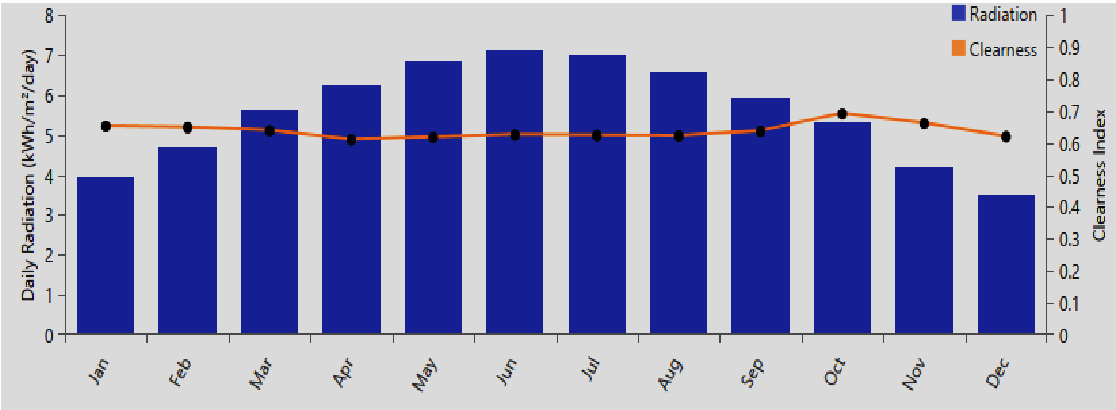
Figure 6. (**a**) Daily load profile of Chak 68-DB. (**b**) Seasonal load profile of Dilmurad Mahar Sindh. (**c**) Seasonal load profile of Mastung Baluchistan. (**d**) Seasonal load profile of Shahi Bala KPK.

2.3. Resource Assessment

The proposed rural areas are located in all four provinces of Pakistan. The solar and wind resource data is fetched from the National Renewable Energy Laboratory (NREL) database using co-ordinates of the areas, and biomass resource data is estimated during site surveys.

2.3.1. Solar Resource Potential

Pakistan is rich in solar resources and most parts of the country get a huge amount of radiation throughout the year. The solar irradiance data was fetched from the NREL database using the latitude and longitude of the area. The solar irradiance data also includes the clearness index and direct rays including diffused lights. Figure 7a shows the monthly average solar irradiance at the Punjab location is 5.57 kWh/m²/day and the monthly average clearness index is 0.65. Figure 7b shows the monthly average solar irradiance at the Sindh location is 5.64 kWh/m²/day and the monthly average clearness index is 0.63. Figure 7c shows the monthly average solar irradiance at the Baluchistan location is 5.79 kWh/m²/day and monthly average clearness index is 0.70. Figure 7d shows the monthly average solar irradiance at the KPK location is 4.93 kWh/m²/day and monthly average clearness index is 0.55. Here, it is seen that the maximum solar insolation is recorded in Baluchistan, providing a beneficial location for a solar-based microgrid, and the least insolation is seen in Kpk with the lowest clearness index, which means here the days would be less sunny and more cloudy. The maximum solar insolation can be seen in the month of June when solar provides maximum energy to the system at all four locations.



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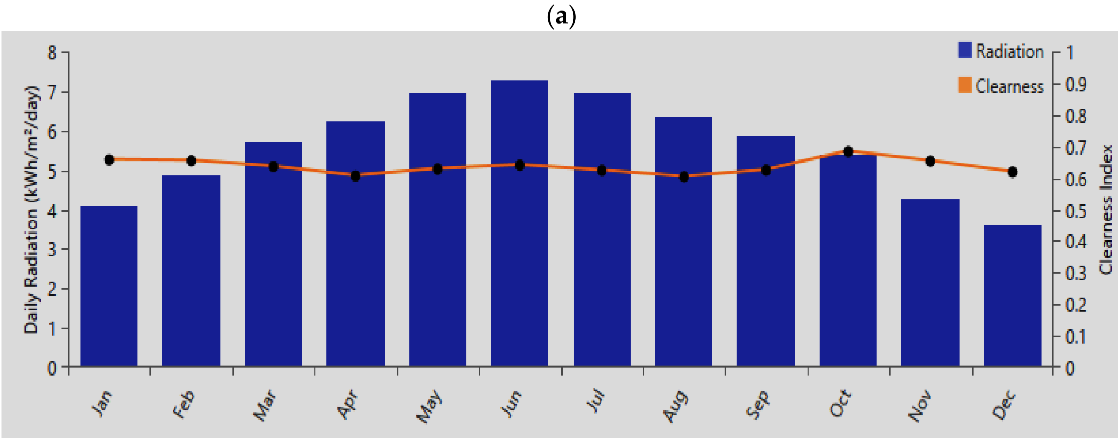

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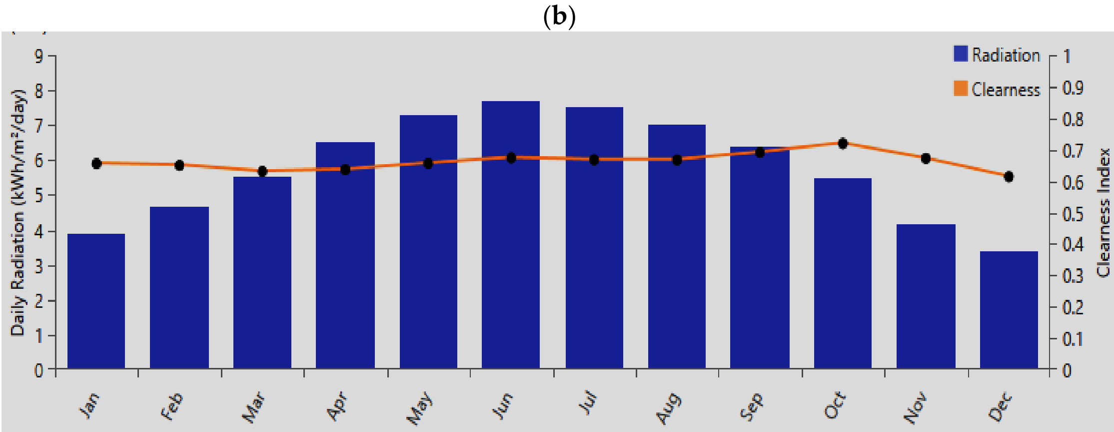

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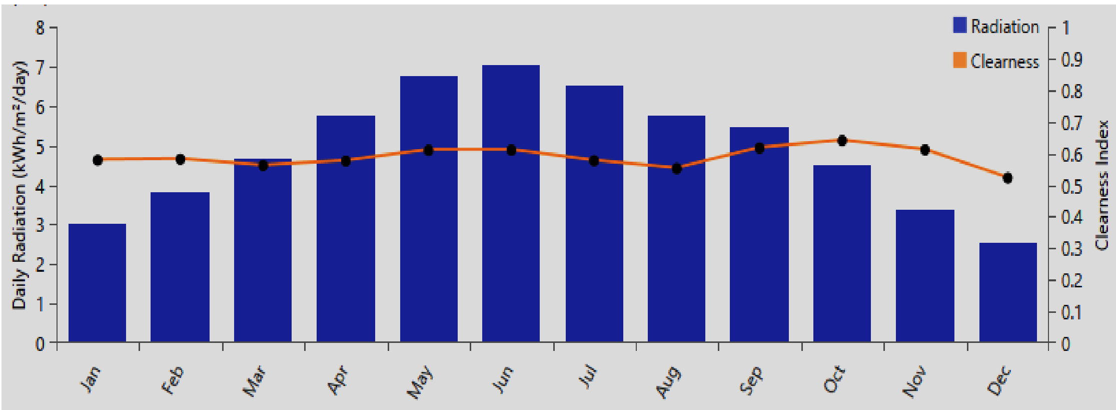

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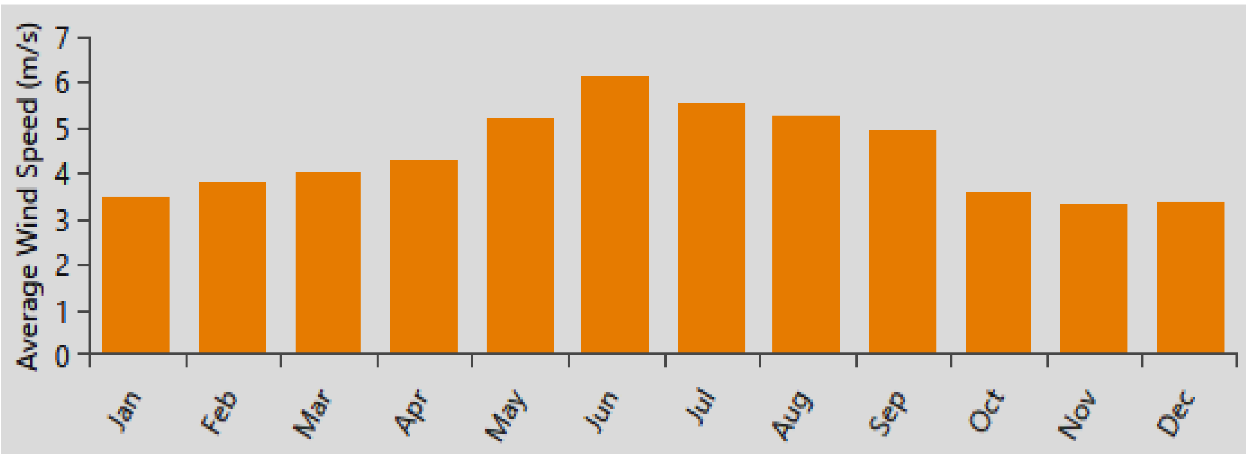
Figure 7. (**a**) Solar irradiance for the whole year for Chak 68 DB Punjab. (**b**) Solar irradiance for the whole year for Dilmurad Mahar Sindh. (**c**) Solar irradiance for the whole year for Mastung Baluchistan. (**d**) Solar irradiance for the whole year for Shahi Bala KPK.

2.3.2. Wind Resource Potential

Pakistan's wind potential is very high in some parts of Sindh, Baluchistan and across the costal line where enough energy can be generated. According to the survey, Pakistan has 20 GW potential through wind at various locations across the country [44].

The wind resource data of the proposed rural villages is fetched from the NREL by using the area's latitude and longitude. The wind potential is enough to generate electrical energy through a wind turbine. The wind resource data for all proposed locations is shown in Figure 8a–d. The maximum wind is recorded in the month of June at 6.14 m/sec and 6.34 m/sec in Punjab and Sindh, respectively. Whereas in Baluchistan and KPK, the maximum wind speed is recorded in the month of May with a magnitude of 5.2 m/sec and 3.4 m/sec, respectively. Although the average wind speed in KPK is not too high, it still lies above the cut-in speed of the selected wind turbine, i.e., 2.7 m/sec.



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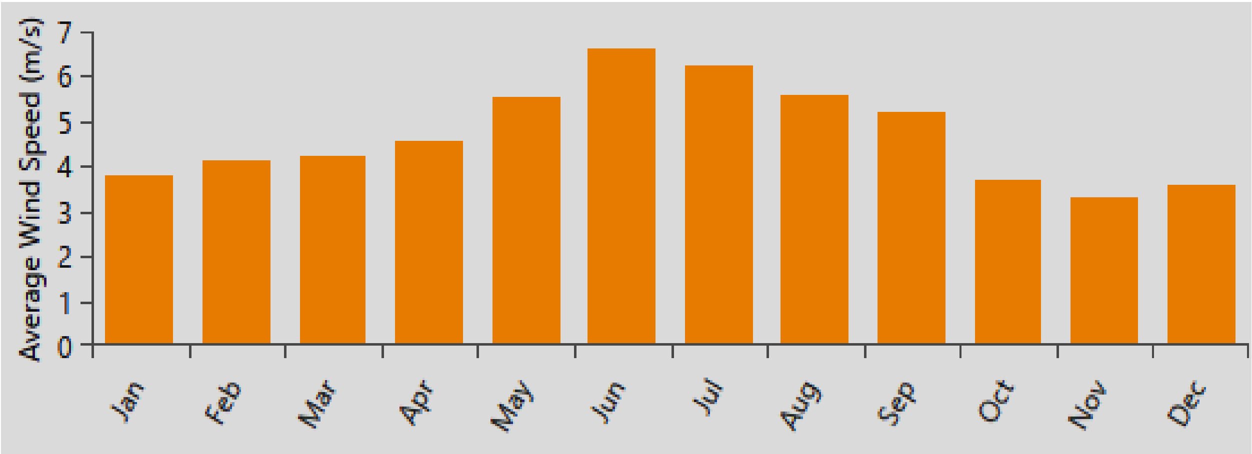

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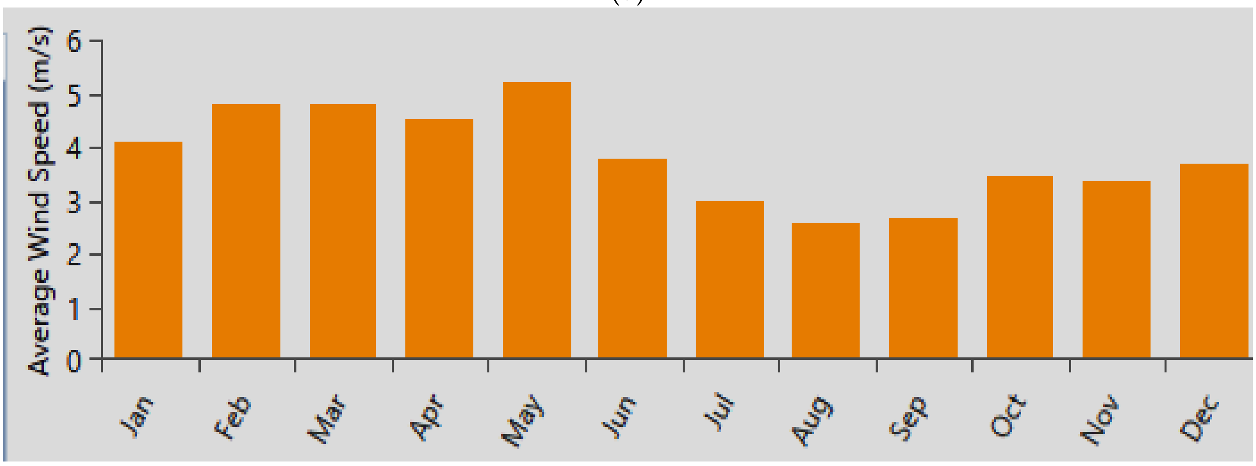

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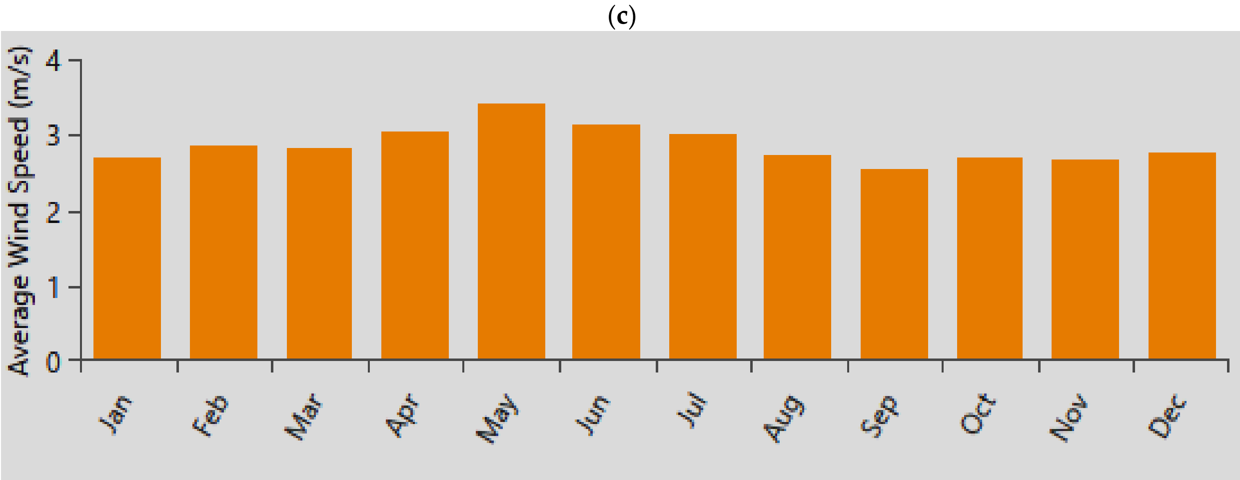

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Figure 8. (**a**) Average wind speed over the year for Chak 68 DB. (**b**) Average wind speed over the year for Dilmurad Mahar Sindh. (**c**) Average wind speed over the year for Mastung Baluchistan. (**d**). Average wind speed over the year for Shahi Bala KPK.

2.3.3. Biomass Potential

An agricultural country like Pakistan is full of biomass resources. The recent biomass-mapping project disclosed huge reserves of biomass resources in the province of Punjab, including crops left over and animal manure. In this study, we are focusing on animal manure available in the vicinity of the proposed location. There were around 500 cows in total at the proposed location in Punjab, 250 at the Sindh location, 310 at KPK village and

400 at the location in Baluchistan. And each cow produces 15 to 16 kg manure daily [45]. Animal dung is estimated and given in Table 5.

Table 5. Per day manure production at the proposed locations.

Number of Cows	Per Head Animal Waste Production (kg/day)	Total Bio-Waste Production Per Day
500	16 kg	500 × 16 × 1000 = 8 tons
250	16 kg	250 × 16 × 1000 = 4 tons
310	16 kg	310 × 16 × 1000 = 5.1 tons
400	16 kg	400 × 16 × 1000 = 6.4 tons

2.4. Case Scenarios in terms of Seasonal Variations

2.4.1. Midcareer Impact

The hybrid systems designed for the present load demand and prices include all types of cost like initial investment, running cost, maintenance cost and replacement, as well costs during the entire lifetime of the project. But in the case of high demand, as it continuously grows with time, there will be a need for additional energy production as we have chosen a standalone microgrid that has to feed the communities. For that case, we have considered two scenarios one at the current time with the present load demands of the locals and a second case after 15 years with the increment of 20 percent in the communities' energy load that would require an additional cost during the project lifetime because we have to buy more solar panels and wind turbines to fulfill the increased energy demand. With time, biomass production would vary but we cannot say at the current time it would increase with load growth. So, the tariff of the energy produced would revise in the middle of the project so does the payback period and rate of return. We considered these midcareer scenarios in HOMER to estimate the variations in terms of techno-economic and environmental analysis.

A 20% increase in the load with 10% inflation after 15 years, along with the additional cost of the new resource components in order to meet the increased load demand, has been considered while simulating the project on HOMER. The project life span is 25 years and the overall results in the end include all the initial investments, running and maintenance cost and all other costs that would occur during the life span of the project.

2.4.2. Environmental Effect on the Proposed Hybrid System

As it is clear that renewable resources are intermittent in nature, they cannot be the only dependent source in most countries globally. During summer, we have high temperature variations that could lead to overall PV performance to lower the level in the Sindh and Punjab region. So that affect could be minimized using extra panels or feeding the same load from wind or biomass resources as per availability. Similarly, PV production is reduced in the winter due to the lesser sunlight and reduction in the incident radiation on the panel surfaces. So, this effect is mitigated by the use of an extra battery backup. In the Baluchistan region where the wind effect is more dominant, extra care has to be taken in designing the mechanical structure of wind turbines and PV arrays. Due to high wind impact, wind turbines with lower hub height (10 m) are considered in the study. PV electric power potential across the country is provided in Figure 9.

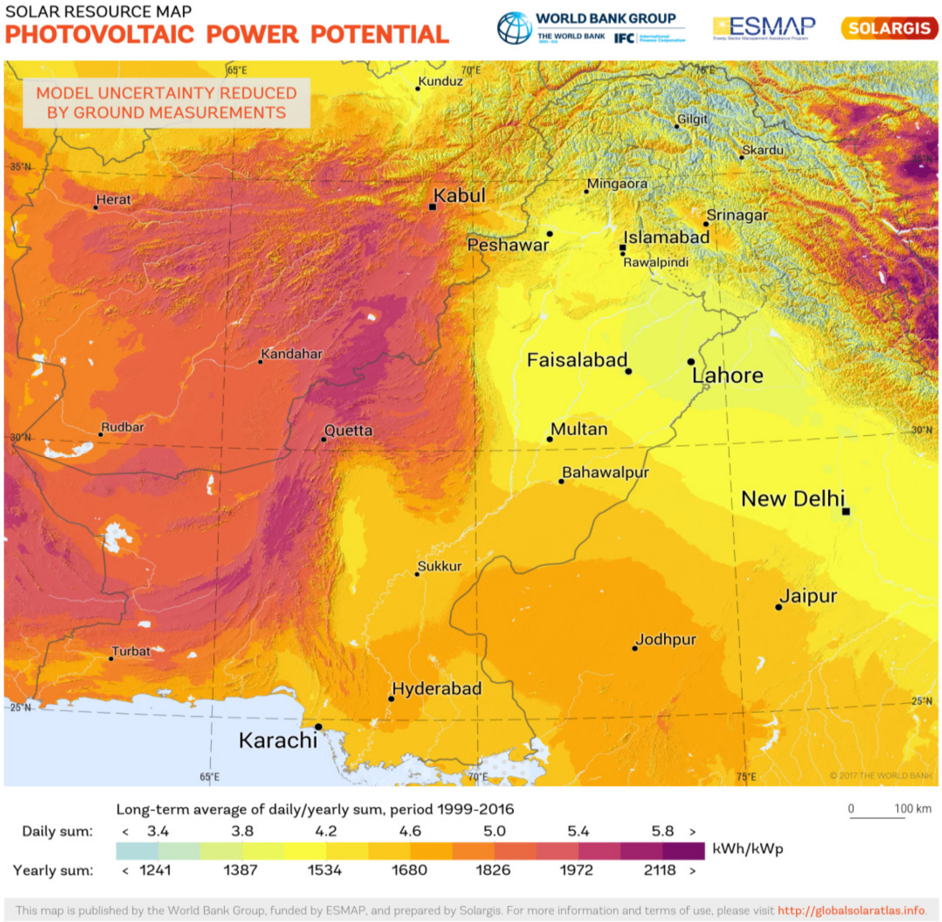


Figure 9. PV Electric potential in Pakistan.

2.4.3. Grid Extension Cost and Tariffs

Remote areas are always located far away from the urban population and have low population density. Due to improper infrastructure, lack of awareness, jobs, and disperse populations, remote areas have a low load factor. These rural locations typically lie far away from the national grid stations. In this study, the proposed locations also lie at a longer distance from the utility grids. The minimum distance that was estimated during site surveys was 16 kMs in the Punjab and remaining regions are a longer distance. In order to evaluate the grid extension feasibility for the selected locations, the grid-extension limit was determined using HOMER while designing the microgrid. Tariff rates, capital cost, and operation and maintenance costs of the transmission line were calculated [46], whereby all the data was provided from the Sindh electric power supply company for a 95 km long transmission line extension in the Sindh region. All values were taken in per km length of the transmission line. Relevant data are provided in Table 6.

Table 6. Transmission line parameters.

Length of Transmission Line	**95.74 kM**	
Capital Cost (million-Pkr)	1864.04	19.47/kM
Operation & Maintenance Cost (million-Pkr)	190.02	1.98/kM
Grid Power Tariff (Pkr)	0.79/kWh	

2.4.4. Climatic Zone Effects and Resource Dominance Region-Wise

Pakistan is known for its different climatic zones that vary from region to region like extreme solar insolation in the lower Punjab and interior Sindh, whereas huge wind potential exists in Baluchistan and some parts of Kpk. This study utilizes remote areas from all these provinces of Pakistan. Although renewables are time dependent and not available all the time and it is really hard to feed a constant load from a single source, either PV or wind resource. But the effect could be minimized in the case of multiple resources or utilizing a greater number of PV or wind resources and a proper energy storage device considering the autonomy of the selected region.

In the system design and from resource availability, Baluchistan and KPK rural areas are dominant in wind resources, so the hybrid systems designed for these locations are wind-dominant hybrid systems and more power is produced from wind resources, while Sindh and Punjab have a major chunk of solar energy available making the proposed hybrid system PV dominant in these remote locations, and thus a large proportion of energy demand is fulfilled from the PV resource.

3. Software Selection

The hybrid optimization model for the electric-renewables (HOMER) tool was selected for the study. HOMER was originally produced by the National Renewable Energy Laboratory (NREL), and it contains a series of power producing elements with multiple options for hybrid system modeling. The user may select any of the power producing elements to model the actual system structure. Depending upon the complexity and size of the system, it may take from a few minutes to several hours to perform thousands of simulations to present the most optimized results. HOMER produces a simpler system design and assists the user in selecting a series of energy techniques as per the financial constraints and data resource input. HOMER gives the following results:

- The proposed hybrid design meets the load requirement or is insufficient
- In what combination energy resources are more favorable for the proposed case
- In the case of a standalone system, a storage backup requirement exists
- Which strategy is more suitable for the designed system?
- Impact of fuel price variation on the overall system

HOMER is used to determine the economic viability and technical feasibility of different hybrid renewable energy systems. The technical feasibility of the designed system was observed on the basis of the capacity shortage factor and zero unmet load, while economic viability was assessed by means of the lowest NPC and least-levelized COE.

HOMER uses two types of dispatch strategies, i.e., cycle charging (CC) and load following (LF) for optimization and simulations. HOMER selects the system that is the most optimum from the given resources and considers energy balance on an hourly basis.

3.1. Simulation

HOMER does simulations on an hourly basis for the entire year, designing a system that meets the load demand over the year. During this, it makes the decision to use the load following or cycle charging technique to run battery storage, as well as a power generator. For any system having battery storage and a power generator, it uses either of the dispatch strategies.

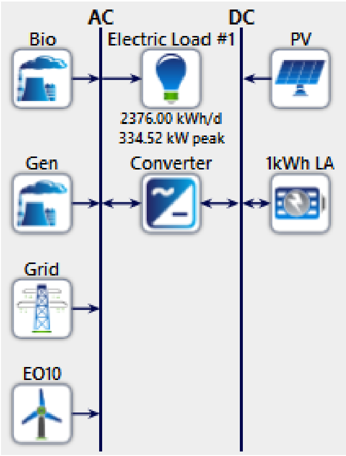
3.2. Optimization

In this part, HOMER imitates various system designs looking for the least NPC and enlists all the possible energy techniques that fulfills energy demand. The purpose of optimization is to find the most appropriate and viable solution.

4. Hybrid System Designing

Hybrid energy storage system is the term usually used for hybrid systems having more than one power producing source with a proper energy storage element. Hybrid systems are more reliable and sustainable as it has more than one energy resource, and if the one power source fails to produce energy like solar in night or cloudy time or wind in off peak hours than the other energy resource could fulfill the energy demand of the system [47].

The proposed hybrid system consists of five components in total, out of which three are energy generating units, i.e., PV solar modules, wind turbines and biogas generator. The other two consist of battery storage and power convertors. Battery storage is used as a backup for no power generation time through solar and wind and also for storing energy when we have surplus generation. Power convertors are used for transforming power from AC to DC and vice versa. Details of each component are given in the subsections. Figure 10a–d demonstrates the schematic illustration of the hybrid power systems.



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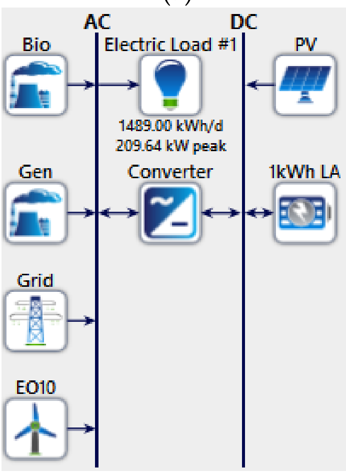

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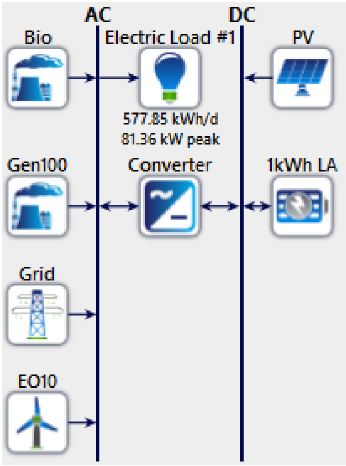

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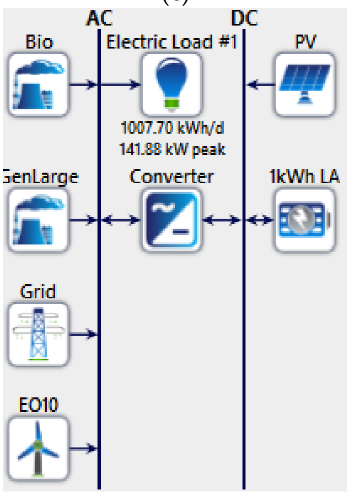

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Figure 10. (**a**) Hybrid system model for Mastung, Balochistan. (**b**) Hybrid system model for Chak 68 DB. (**c**) Hybrid system model for Dilmurad Mahar Sindh 4.1. Solar PV. (**d**) Hybrid system model for Shahi Bala KPK.

Solar photovoltaics belong to the family of semiconductor devices. PVs generate electrical energy when light falls on the surface of the panels through the photovoltaic effect [48]. De-ratting factor is a term that has been used to refer to the power losses with the passage of time due to dust, solar panel degradation, the temperature effect, and other electrical wiring losses. A generic flat-plate polyclinic PV panel with a fixed tracking system is considered in this study, having a power capacity of 250 watts. Capital and replacement costs are taken from local Pakistani distributors. The capital cost per kW of the PV system is taken to be Rs. 50,000. The lifespan of the PV panel is 25 years and the de-rating factor considered is 80%.

Homer uses the following equation for calculating the output PV power of the array

$$P_{PV} = Y_{PV}F_{PV}\left\{\frac{G_T}{G_{T,STC}}\right\}\left[1 + \alpha_P\left(T_c - T_{c,STC}\right)\right] \quad (8)$$

whereas,

Y_{PV} is the rated output-power of PV arrays at standard test conditions (STC)
F_{PV} is the de-rating factor
G_T is the incident radiation at the surface of the PV panel (kW/m²)
$G_{T,STC}$ is the incident-radiation at STC (%/°C)
α_P is the average temperature power co-efficient
T_c is the cell temperature (°C)

$T_{c,STC}$ is the cell-temperature at STC.

4.1. Wind Turbine

Wind turbines are another type of cleaner energy generation that generates electrical energy at the expense of the wind's kinetic energy. When the minimum amount of wind cuts the turbine blades, it starts producing energy and the minimum wind speed is referred to as 'cut-in speed' [48]. The minimum cut-in speed varies with the type and hub height of wind turbines. In our study, we are using the 'EOCYCLE E010' wind turbine because of its lower cut-in speed, i.e., 2.75 m/sec. The lower cut-in speed helps in generating power at a lower wind speed. Figure 11 provides the power curve of the wind generator at a wind speed value. This is a vertical axis wind generator having maximum power capacity of 10 kW. The capital and additional replacement cost is Rs. 600,000 with a lifetime of 20 years

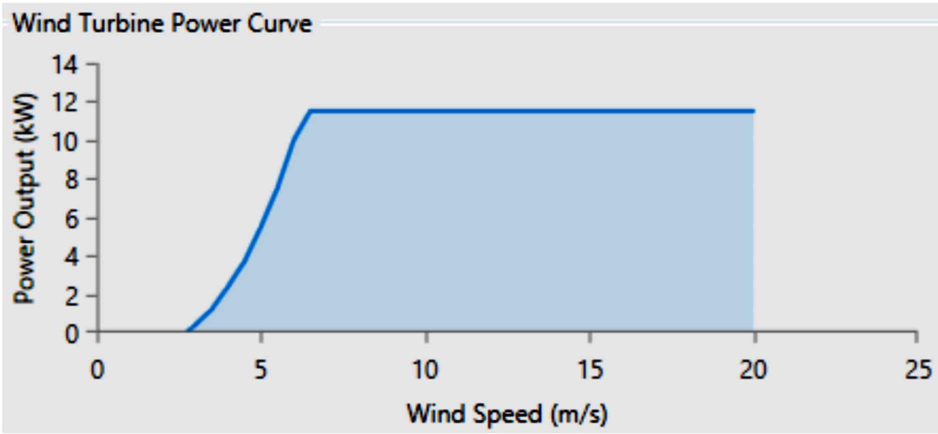

Figure 11. Power curve of wind turbine at varying wind speeds.

4.2. Biogas Generator

A generator is an electrical device that works on the principle of Faraday's law of electromagnetic induction, i.e., "where there will be change in magnetic flux there will be an induced electromotive force (emf)". A bio-generator also produces a form of cleaner energy generation as biogas derived from biomass waste is comparatively much safer environmentally as compared with that from a diesel generator [49]. In this study, a biogas generator is considered whose capacity can be set according to the maximum load demand. The generator has the lowest load ratio of 25% and a lifetime of 20,000 h. Table 7 provides the biogas generator's characteristics, technical constraints and costs.

Table 7. Cost and other constraints of a bio-generator.

Capital Cost (Rs/kilowatt)	**50,000**
Cost of fuel (Rs/ton)	250
Lower heating value (MJ/kg)	5.50
Density (kg/m^3)	0.72
Carbon (%)	5.0
Sulfur (%)	0

4.3. Power Convertors

Power convertors are basically electronically controlled devices that include both rectifiers and invertors to transform electric power into the desired form [49]. Fundamentally, AC and DC are incompatible to deal with in parallel. Therefore, power converters are needed to simultaneously transform and deal with both types. Its fundamental purpose is to transform AC to DC and DC to AC depending upon the need of the power system. The capital and replacement cost is determined to be Rs. 30,000 with a lifetime of 15 years. The relative capacity and efficiency of the power convertors is 100% and 90%, correspondingly.

4.4. Storage Batteries

Batteries are the purest form of energy storage and act as a secondary power source. Batteries store electrical energy in the form of chemical energy. Wheread solar and wind resources are not continuous and their production varies, depending on the area topography and time. So, battery storage is an essential element while designing a hybrid power system based on renewable resources [47]. In a PV, wind systems power is not generating all the time due to the intermittency of PV and wind resources, so for hours when no power is generating, batteries are needed to provide power, which are charged when excess power is generated. Battery storage can also provide the necessary amount of high current surges required by motors and refrigerators.

In this study, 12 V lead-acid deep cycle batteries are considered. Table 8 demonstrates the technical specifications of the battery.

Table 8. Cost and other parameters of Battery.

Parameters	Values
Capital cost (Rs)	20,000
Replacement cost (Rs)	14,000
Initial state of charge SOC (%)	100
Minimum SOC (%)	40
Maximum Discharge current (A)	500
Nominal Capacity (kWh)	01
Life (years)	05

4.5. Diesel Generator

Whichever generator type is used, the mechanism is the same but with a different input resource. Here, we fed the generator with diesel fuel to produce power and in the case bio-generator biogas is needed for producing electrical energy [49]. An auto size diesel generator is also considered in the simulations to analyze how much carbon emissions are saved through the use of renewables in the microgrid models of the proposed locations. The fuel price applied is 240 pkr per liter. The capital cost for the diesel generator is taken from local market as 50,000 pkr per kW.

4.6. Grid Extension

For remote locations, typically, the distance between the proposed location and the transmission grid is estimated to analyze whether extending the transmission line to the particular area is a feasible approach techno-economically or an individual microgrid scheme based on renewable energy would be a favorable approach. HOMER estimated the grid extension limit for the remote location, and if the area lies within that limit than the extension of the transmission line would a favorable approach.

5. Results and Discussions

In order to design a hybrid system based microgrid for the proposed location, the HOMER tool is utilized and considers all available renewable resources, along with a diesel generator and grid extension, to evaluate which approach would be more feasible in terms of environment stability and techno-economic parameters. HOMER does thousands of simulations with different combinations of hybrid models, and gives the best possible solution based on the provided data. HOMER determines the least net present cost NPC and minimum levelized cost of energy COE. The detailed analysis of the results for each location is provided below.

5.1. Chak 68 DB Punjab

In this hybrid system, for the most optimized microgrid design, HOMER chose a 146 kW PV array and 20 EO10 wind turbine, each with the capacity of a 10 kW and 108 kW system converter, respectively; and a 200 kW bio-generator followed by the dispatch strategy HOMER cycle charging with a battery backup of 558 kWh for the no production time from PV and wind. Electrical energy production from each renewable resource is provided in Figure 12. The figure clearly shows the major contribution of wind resources as the area has more wind potential at the time of energy demand; moreover, all the base load is initially met with biomass resources due to the constant load requirement for the base load. One-day autonomy is considered for the battery bank system and state of charge at various points of time throughout the year, as presented in Figure 13.

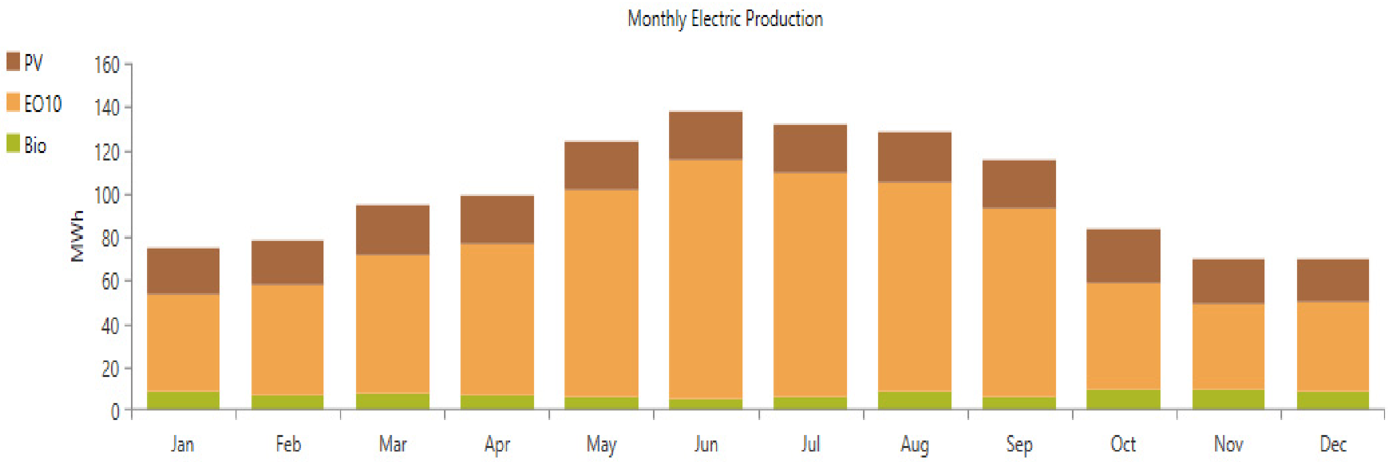

Figure 12. (Annual Power production from all renewables).

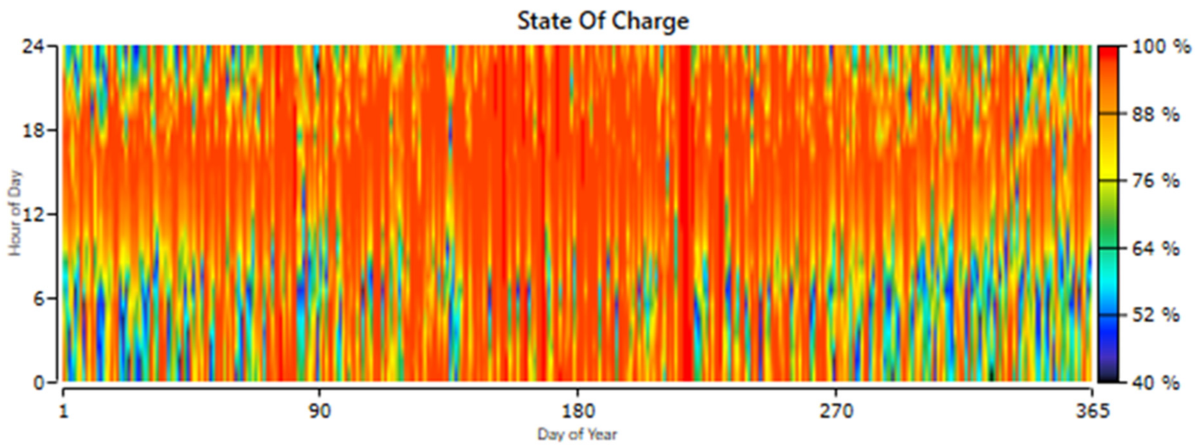

Figure 13. (Annual Battery state of charge).

Figure 14 shows the power production from wind turbines. The most wind power generation is between the months of March till August as the summer season has high wind energy availability. Further, more production occurred in the daytime throughout the year with low wind availability during nighttime. Figure 15 shows PV production throughout the year. Both solar and wind power production occurs in the daytime, saving a lot of energy for the nighttime in the battery backup system. All the stored energy is used during the night when no production is being produced from solar or wind.

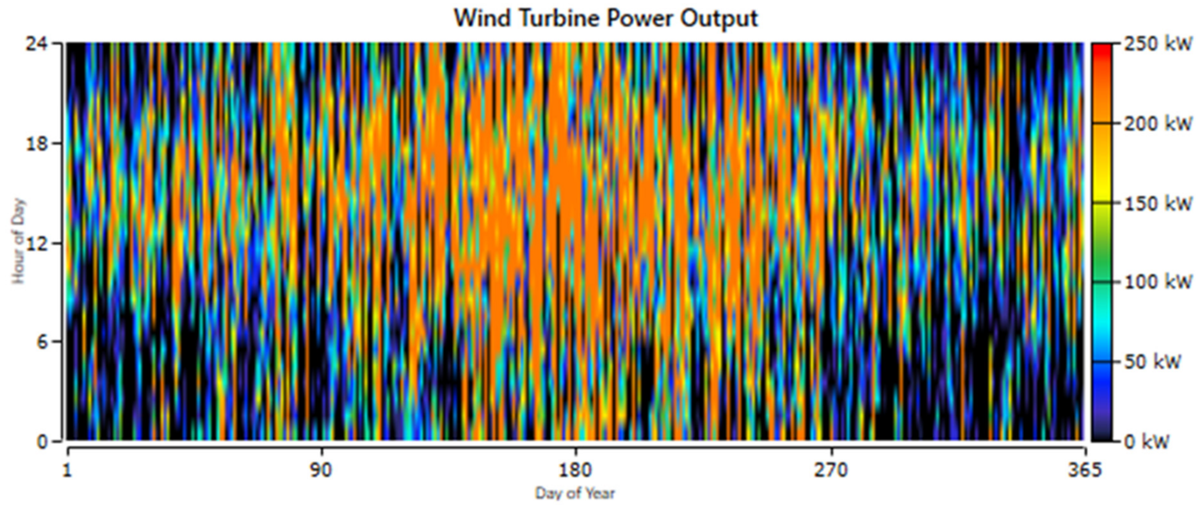

Figure 14. (Wind power production throughout the year).

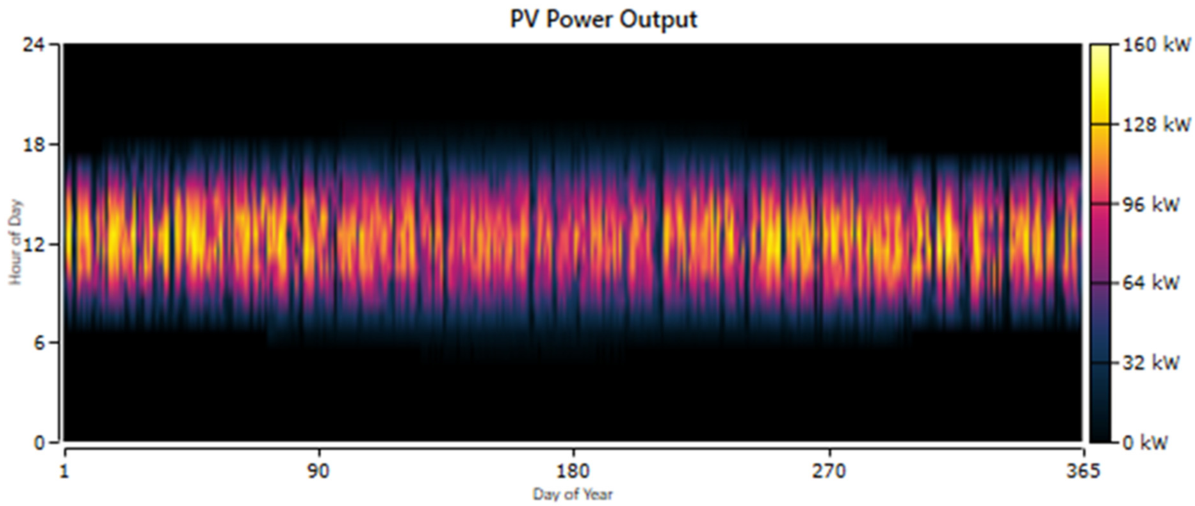

Figure 15. (PV power production throughout the year).

Homer does not consider grid extension because the average distance to the remote location was more than 16 km from the national grid whereas the grid extension limit for this remote location is 2.19 km, as shown in Figure 16. Therefore, instead of extending the transmission lines to the proposed location, a microgrid installation based on a hybrid renewable power system is found to be the most feasible approach based on technical, environmental and economical parameters. Moreover, tons of harmful emissions would be saved from a renewables-based hybrid power system.

For the selected location, we compared the cash flow of the most optimum hybrid system as the proposed case, with the power system based on a diesel generator as a base case, for the entire life of the project. The comparison results are shown in Figure 17. There is a huge difference between the thyroid cases. All the detailed cost parameters including COE per unit of electricity, operational and maintenance cost, NPC, initial capital cost and carbon emissions saved for the proposed case are provided in Table 9.

Table 9. (Cost parameters for all four proposed locations).

Remote Locations	Initial Capital Cost (PKR)	Operating Cost (PKR)	COE (PKR/KWh)	Total NPC (PKR)	Carbon Emissions Saved (kg/year)	Payback Period (years)
Chak 68 DB, Punjab	100.881 M	4.168 M	14.85	104.323 M	538,664	3.1
Dilmurad Maharr, Sindh	38.266 M	1.529 M	14.27	38.896 M	238,361	1.9
Shahi Bala, KPK	89.358 M	4.613 M	21.94	104.314 M	325,718	2.8
Mastung, Baluchistan	180.973 M	6.473 M	15.54	174.175 M	805,288	4.1

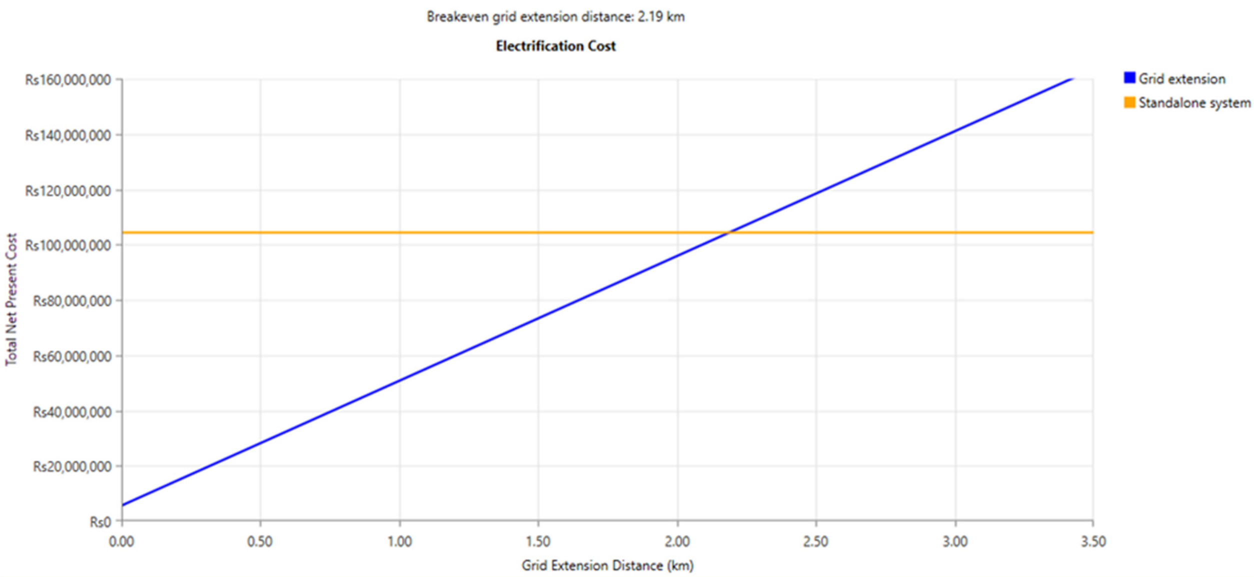

Figure 16. (Grid-extension limit estimation).

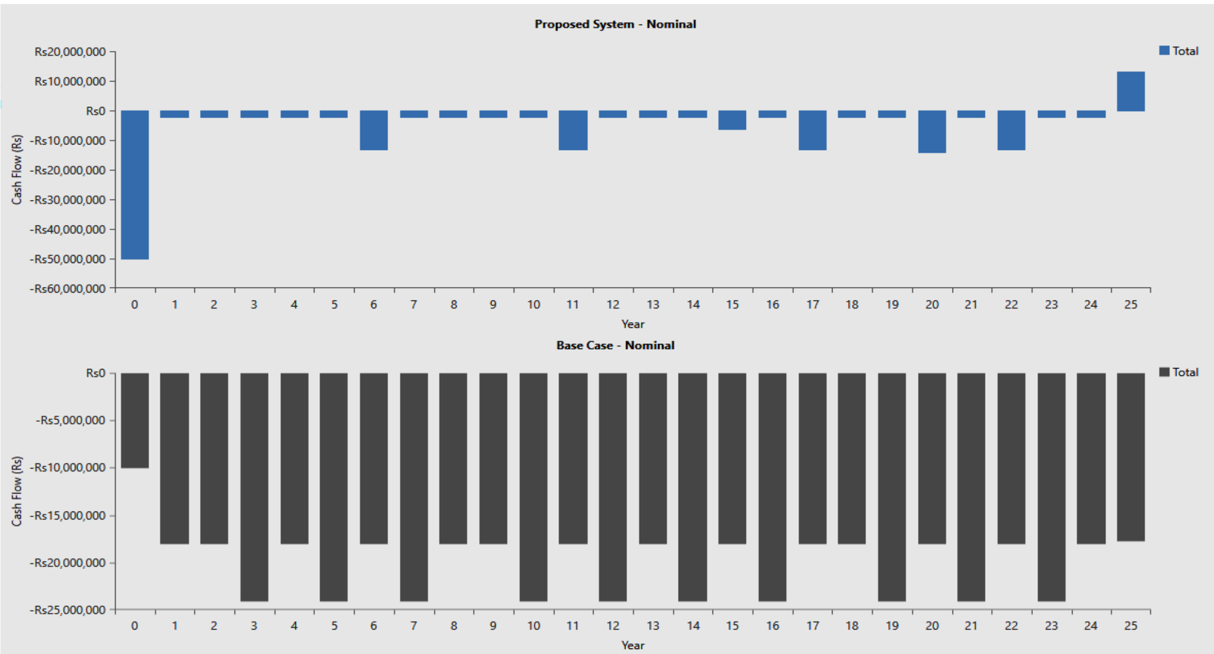

Figure 17. Cash flow for base and proposed case for Punjab.

5.2. Dilmurad Mahar Sindh

For the most optimized hybrid power system, HOMER considered a 54.2 kW PV array size, 7 EO10 wind turbines with the capacity of 10 kW each, a 44.8 kW system converter for power conversions from AC to DC and vice versa, and a biogas generator with the auto set capacity of 82 kW followed by HOMER cycle charging having a battery backup of 211 kWh for the night loads. Energy production from each renewable resource is provided in Figure 18. The figure clearly shows the major contribution of wind resources as the area has more wind potential at the time of energy demand; moreover, all the base load is initially met with the biomass resource due to the constant load requirement for the base load. One-day autonomy is considered for the battery bank system and state of charge at various points of time throughout the year, as presented in Figure 19.

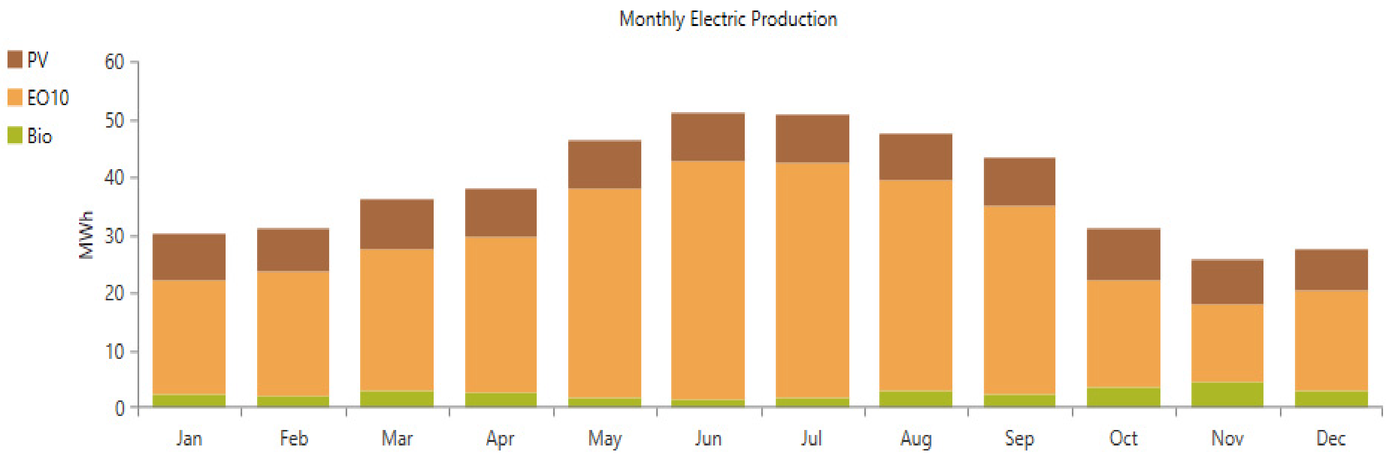

Figure 18. Annually Power generation from all renewables.

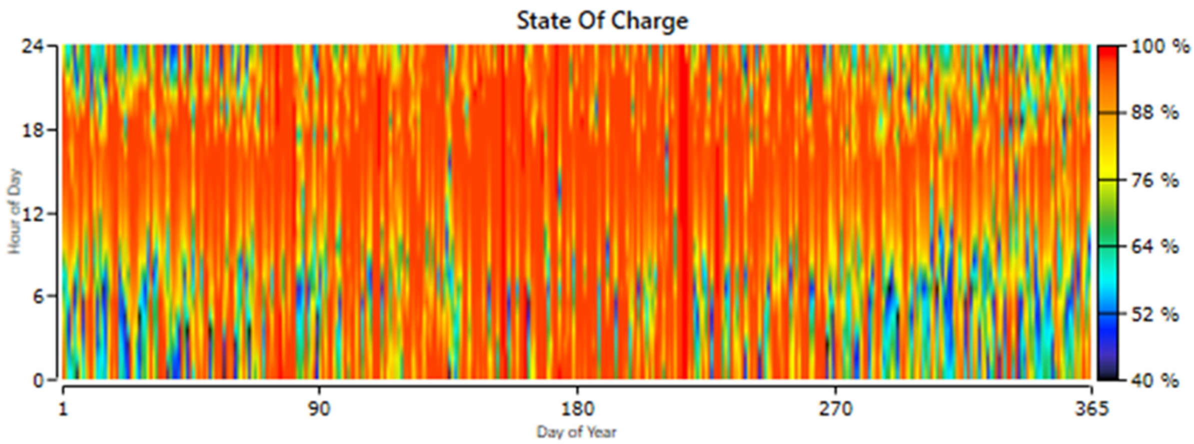

Figure 19. Annually charge state of Battery.

Figure 20 shows the power production from wind turbines. The most wind power generation is between the months of March till August as this the summer season with high wind energy availability. Further, more production occurred in the daytime throughout the year as low wind is available during nighttime. Figure 21 shows the PV production throughout the year. Both solar and wind power production occurs in the daytime, saving a lot of energy for the nighttime in the battery backup system. All the stored energy is used in the night when no production is produced from solar or wind.

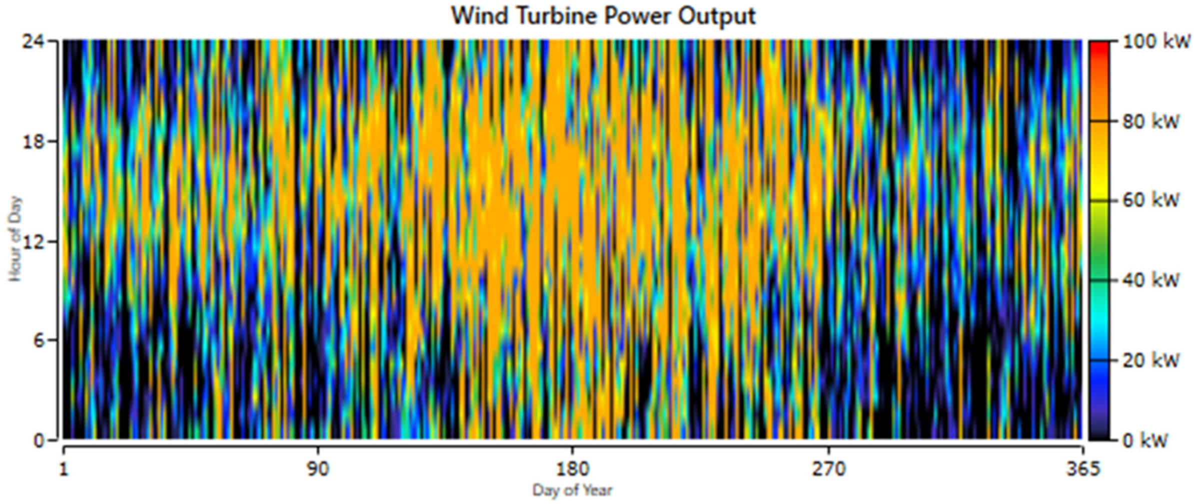

Figure 20. Annual wind power generation.

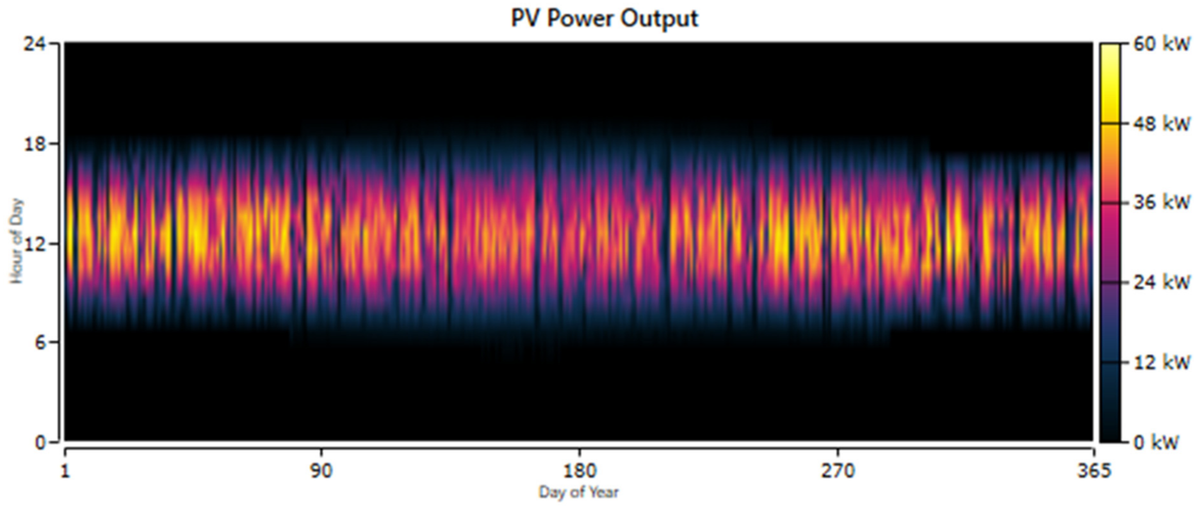

Figure 21. Yearly PV power production.

Homer does not consider grid extension because the average distance to the remote location was more than 16 km from the national grid whereas the grid extension limit for this remote location was 0.81 km, as shown in Figure 22. The grid extension limit shows if the distance between the transmission grid and proposed location lies within this limit, in which case extending transmission lines to the remote area would be a feasible approach. Therefore, instead of extending transmission lines to the proposed location, a microgrid installation based on a hybrid renewable power system is found to be the most feasible approach based on technical, environmental and economic parameters. And tons of harmful emissions have been saved from the renewable based hybrid power system.

For the selected location, we have compared the cash flow of the most optimum hybrid system taking as the nominal case, with the power system based on the diesel generator as a base case, for the entire life of the project. The comparison results are shown in Figure 23. There is a huge difference in both cases. All the detailed cost parameters including COE per unit of electricity, operational and maintenance cost, NPC, initial capital cost and carbon emissions saved for the nominal case are provided in Table 9.

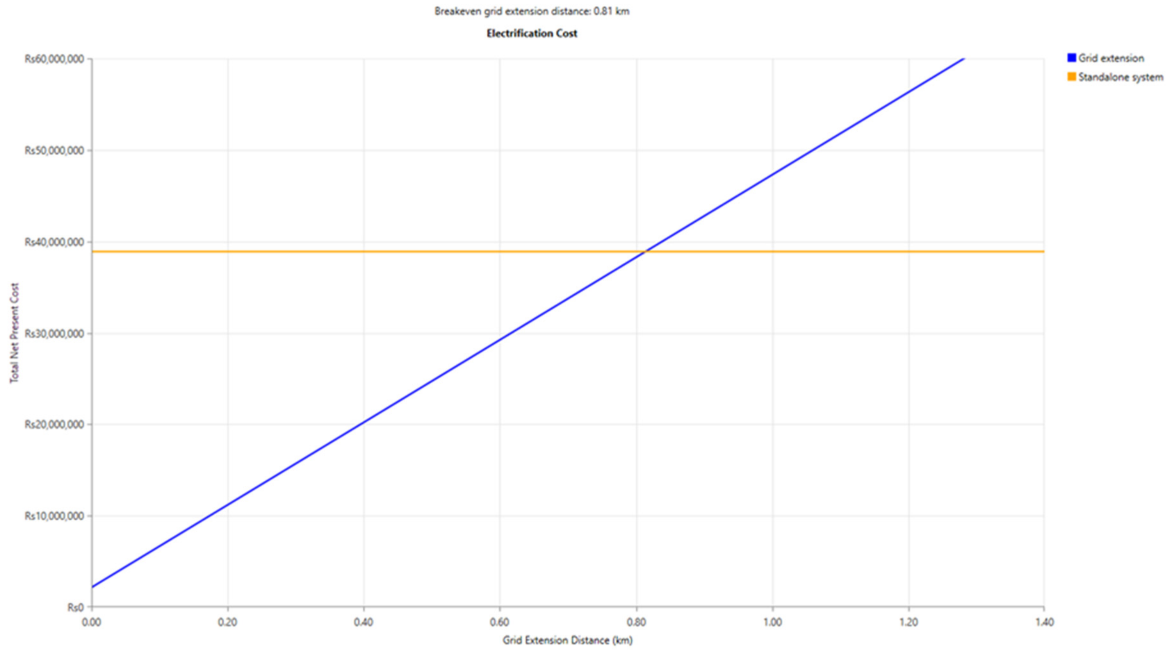

Figure 22. Estimation of National Grid-extension limit.

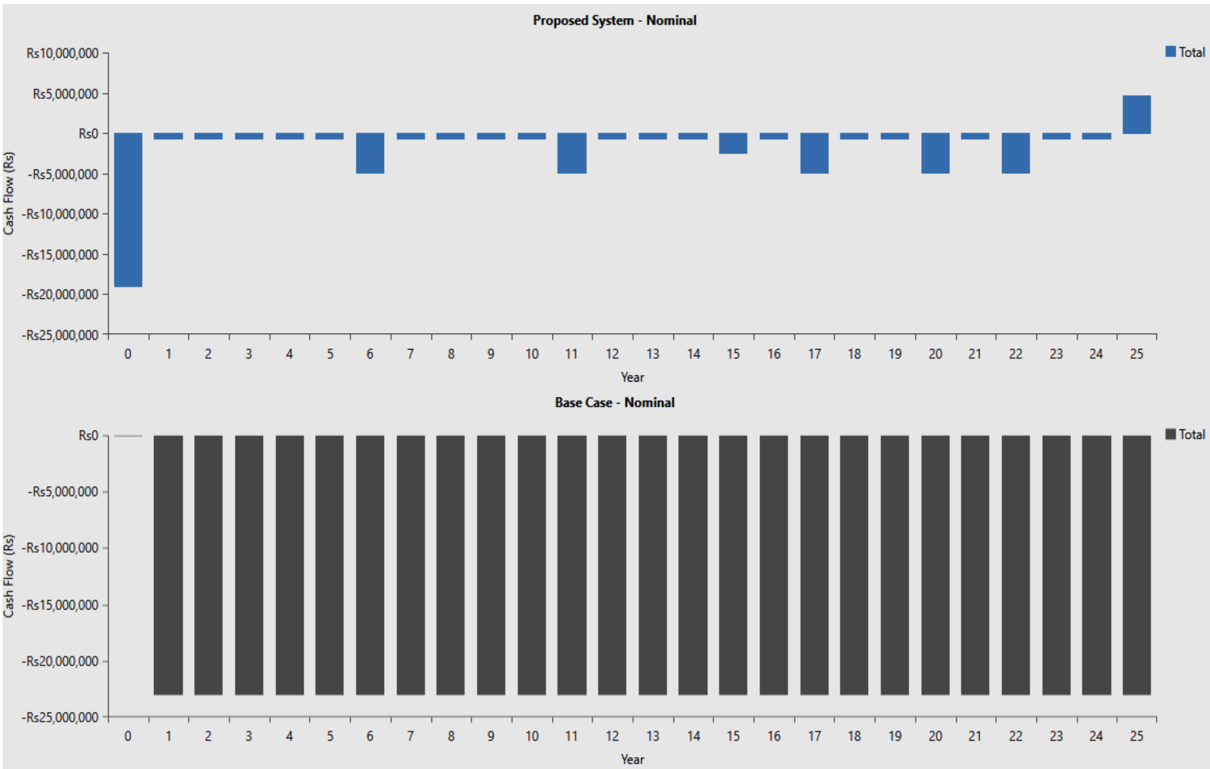

Figure 23. Cash flow comparison for Sindh location.

5.3. Shahi Bala KPK

For this location, HOMER used the most optimized microgrid with a system architecture that consists of a 204 kW PV array, 10 Eocycle EO10 wind turbines each with a 10 kW capacity, 93 kW system converter, and a biogas auto genset with a capacity of 150 kW followed by HOMER cycle charging with a battery bank of 575 kWh for the no generation time. Energy production from renewable resources is provided in Figure 24. The figure clearly shows the major contribution of wind resources as the area has more wind potential at the time of energy demand moreover all the base load is initially met with biomass resources due to the constant load requirement for the base load. One-day autonomy is considered for the battery bank system and state of charge at various points of time throughout the year, as presented in Figure 25.

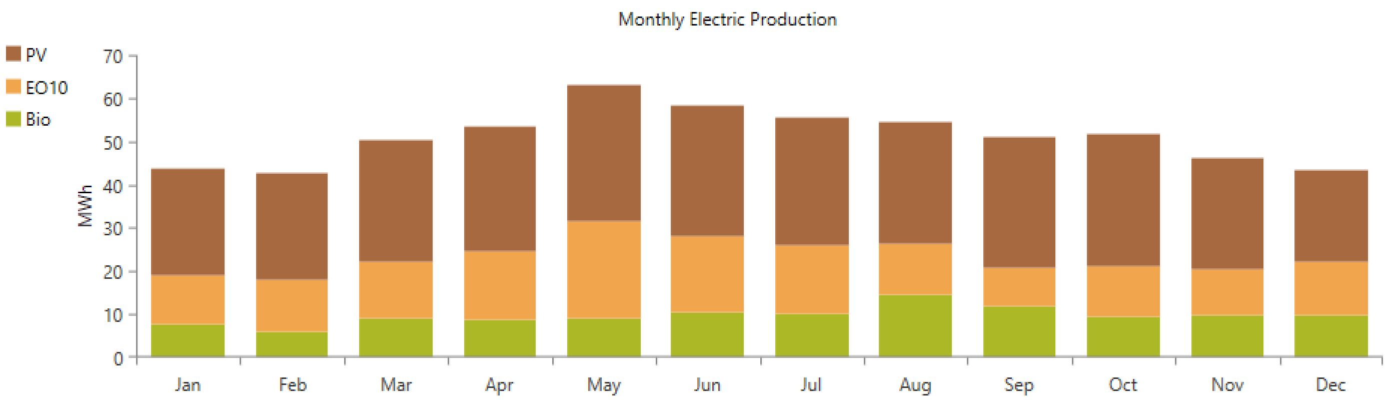

Figure 24. Electric power generation from all available renewable resources.

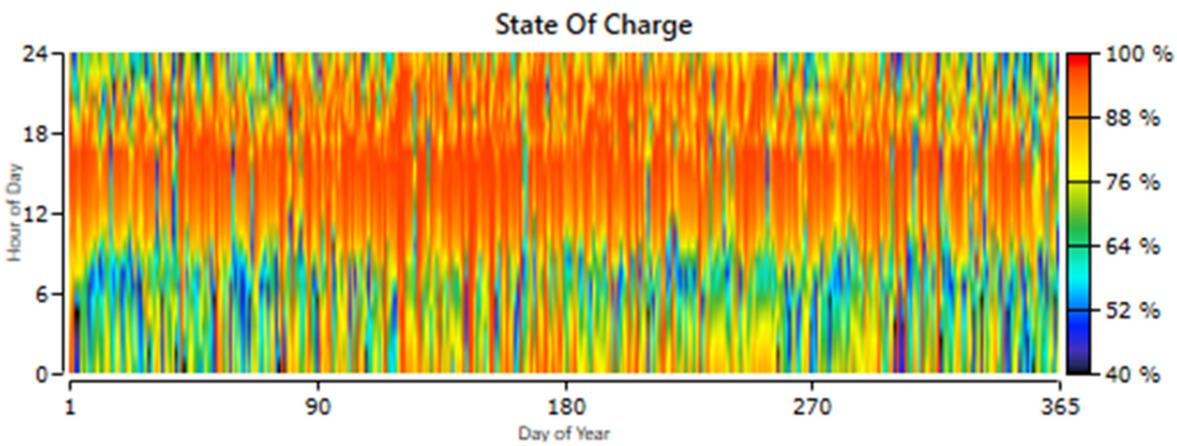

Figure 25. Yearly battery state of charge.

Figure 26 shows the power production from wind turbines. The most wind power generation is between the months of March till August as the summer season has high wind energy availability. Further, more production occurred in the daytime throughout the year as low wind is available during nighttime. Figure 27 shows the PV production throughout the year. Both solar and wind power production occurs in the daytime, saving a lot of energy for the nighttime in the battery backup system. All the stored energy is used in the night when no production is produced from solar or wind.

Homer does not consider grid extension because the average distance of the remote location was more than 16 km from the national grid whereas the grid extension limit for this remote location is 2.33 km as shown in Figure 28. Therefore, instead of extending transmission lines to the proposed location, microgrid installation based on a hybrid renewable power system is found to be the most feasible approach based on technical, environmental and economical parameters. Tons of harmful emissions are saved from the renewables-based hybrid power system.

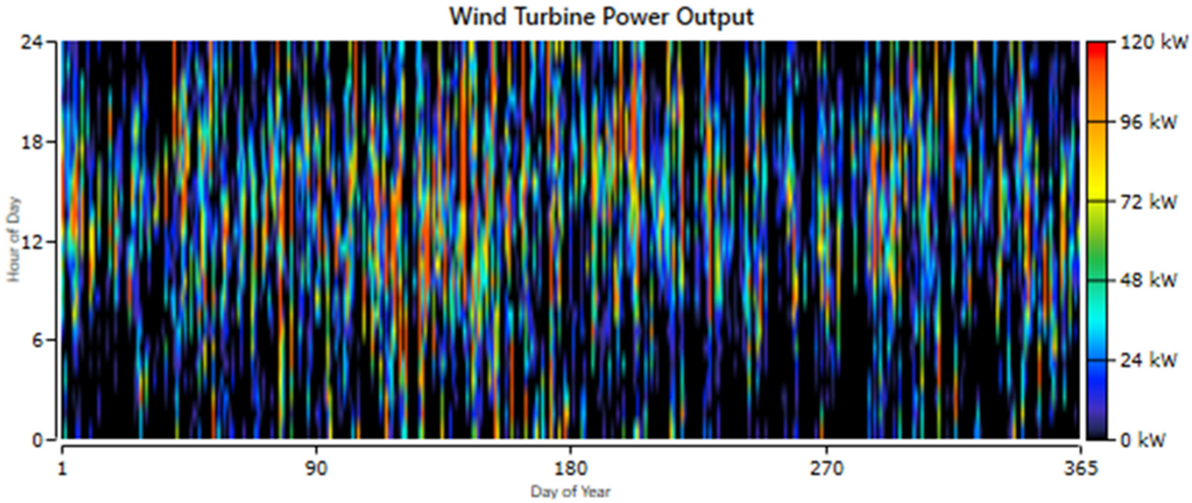

Figure 26. Annual electric power production through wind for KPK.

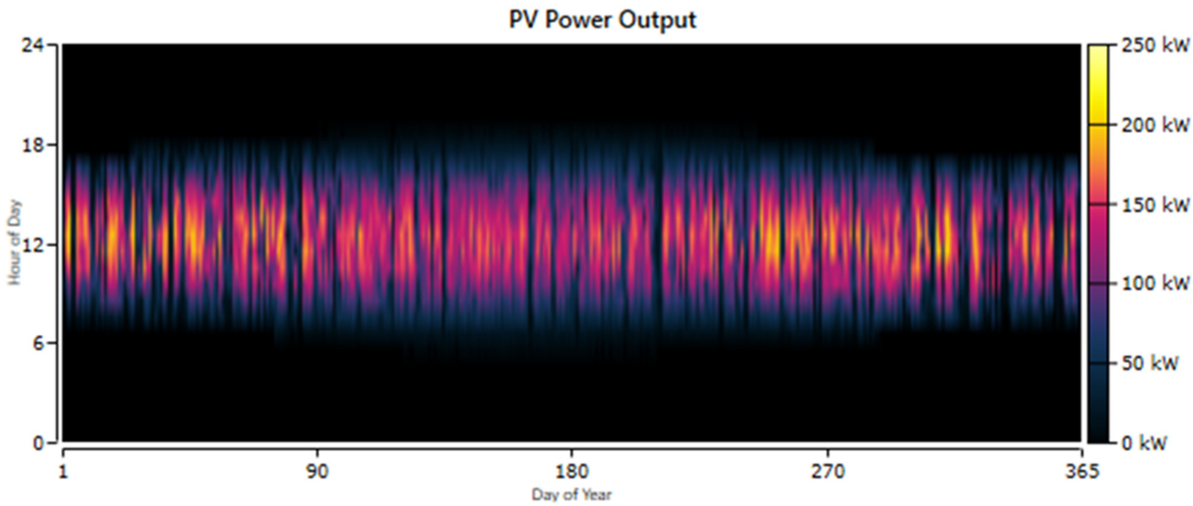

Figure 27. Yearly electric power generation from PV.

For the selected location, we have compared the cash flow of the most optimum hybrid system taking as the nominal case, with the power system based on the diesel generator as a base case, for the entire life of the project. The comparison results are shown in Figure 29. There is a huge difference in both cases. All the detailed cost parameters including COE per unit of electricity, operational and maintenance cost, NPC, initial capital cost and carbon emissions saved for the nominal case are provided in Table 8.

5.4. Mastung Baluchistan

For the selected remote location, HOMER considered the most optimized hybrid system with a system architecture of a 345 kW PV array, 16 Eocycle EO10 wind turbines having a 10 kW rating each, 252 kW system converter, and 80 kW biogas generator followed by the dispatch strategy of HOMER cycle charging having a battery backup of 1652 kWh. Energy production from each renewable resource is provided in Figure 30. Figure 30 clearly shows the major contribution of wind resources as the area has more wind potential at the time of energy demand; moreover, all the base load is initially met with biomass resources due to the constant load requirement for the base load. One-day autonomy is considered for the battery bank system, and the state of charge at various points of time throughout the year is presented in Figure 31.

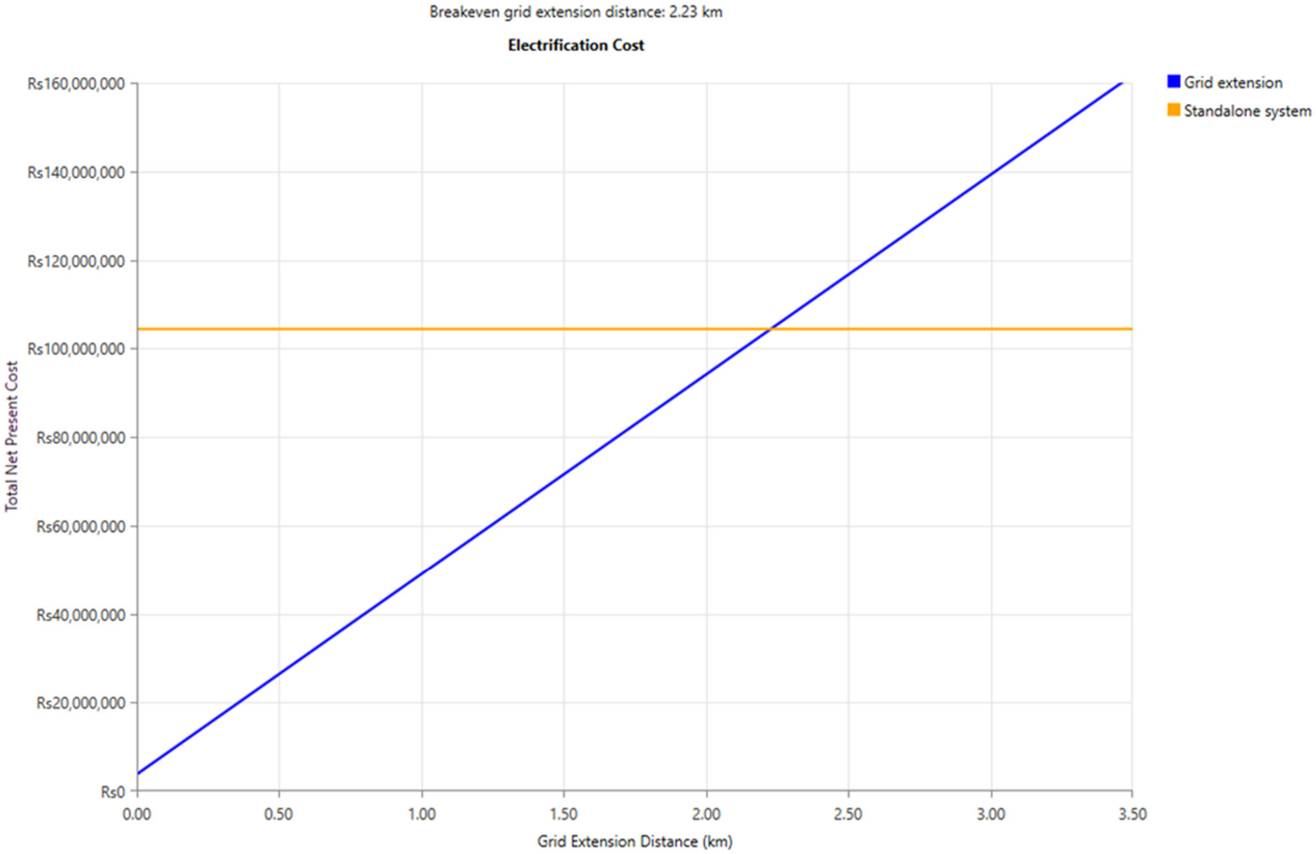

Figure 28. Estimation of power transmission Grid-extension limit.

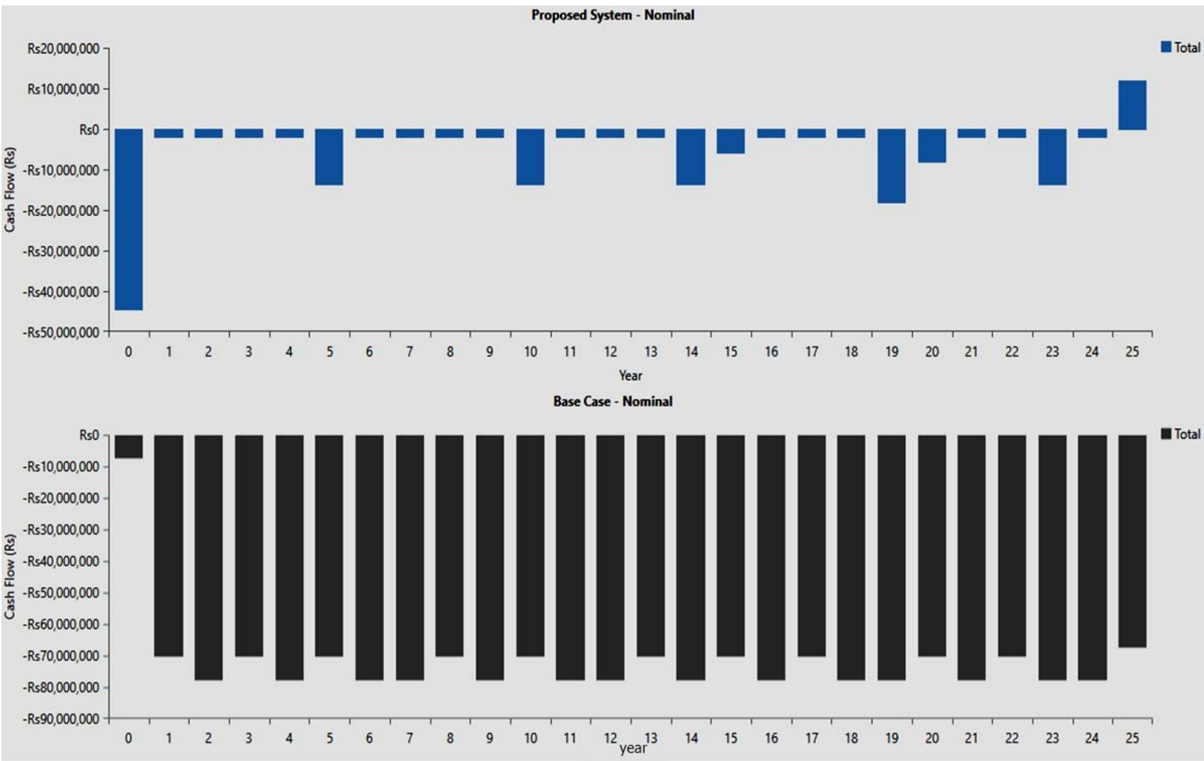

Figure 29. Cash flow comparison for the proposed KPK location.

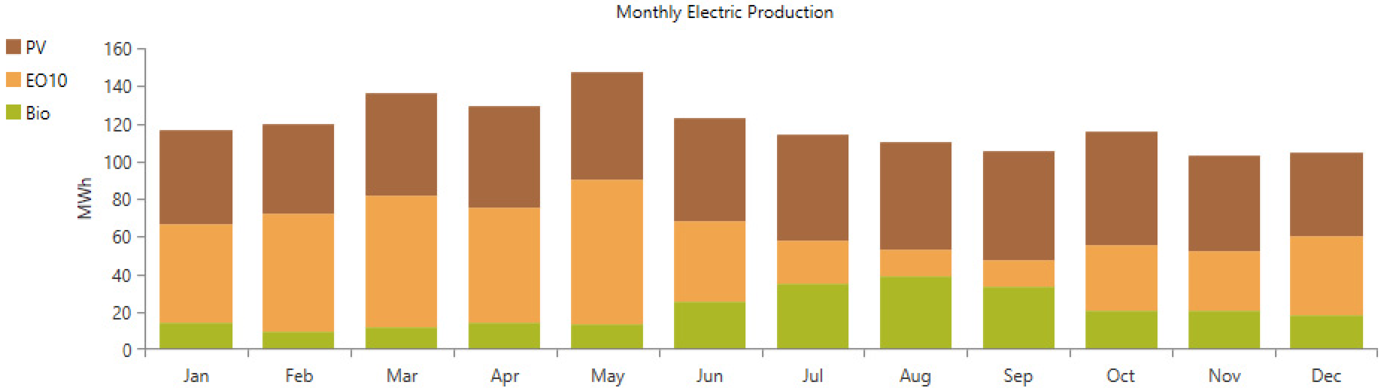

Figure 30. Yearly electric power production from all renewables.

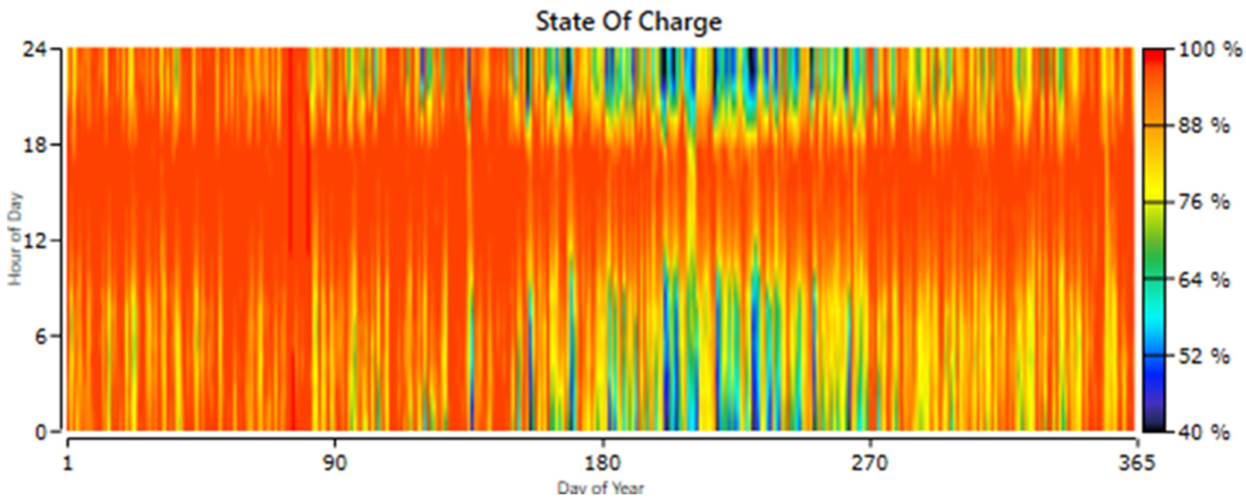

Figure 31. Annual Battery state of charge.

Figure 32 shows the power production from wind turbines. The most wind power generation is between the months of March till August as the summer season has high wind energy availability. Further, more production occurred in the daytime throughout the year as low wind is available during nighttime. Figure 33 shows the PV production throughout the year. Both solar and wind power production occur in the daytime, saving a lot of energy for the nighttime in the battery backup system. All the stored energy is used in the night when no power production from solar or wind.

Homer does not consider grid extension because the average distance to the remote location was more than 16 km from the national grid whereas the grid extension limit for this remote location is 3.66 km, as shown in Figure 34. Therefore, instead of extending transmission lines to the proposed location, the microgrid installation based on the hybrid renewable power system is found to be the most feasible approach based on technical, environmental and economical parameters. Further tons of harmful emissions would be saved from the renewables-based hybrid power system.

For the selected location, we have compared the cash flow of the most optimum hybrid system taken as the nominal case, with the power system based on a diesel generator as a base case, for the entire life of the project. The comparison results are shown in Figure 35. There is a huge difference in both cases. All the detailed cost parameters including COE per unit of electricity, operational and maintenance cost, NPC, initial capital cost and carbon emissions saved for the nominal case are provided in Table 9. Further, all the technical parameters including system architecture and financial terms are attached as evidence of the actual results fetched from HOMER and provided in Figure 36.

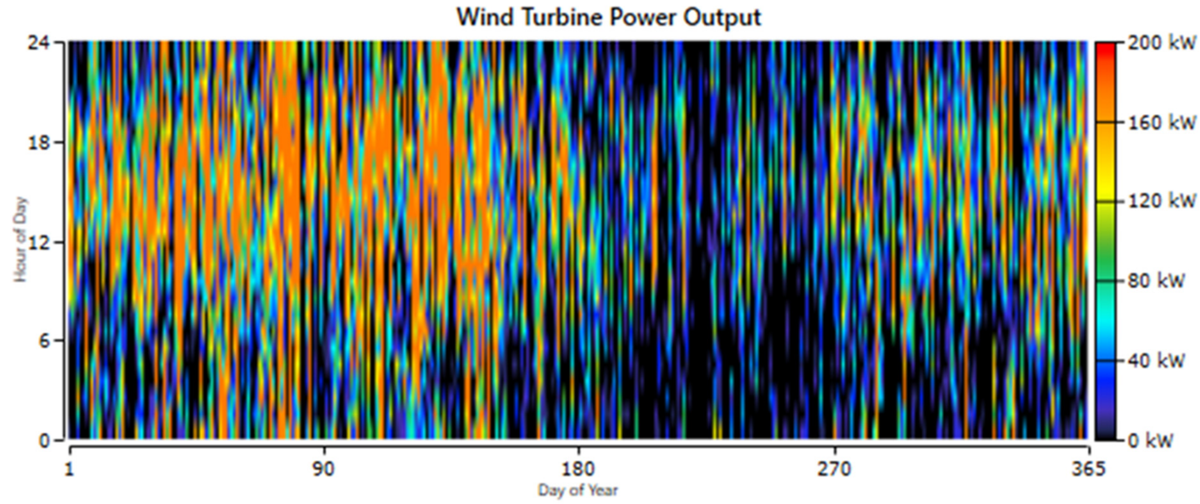

Figure 32. Wind power generation annually.

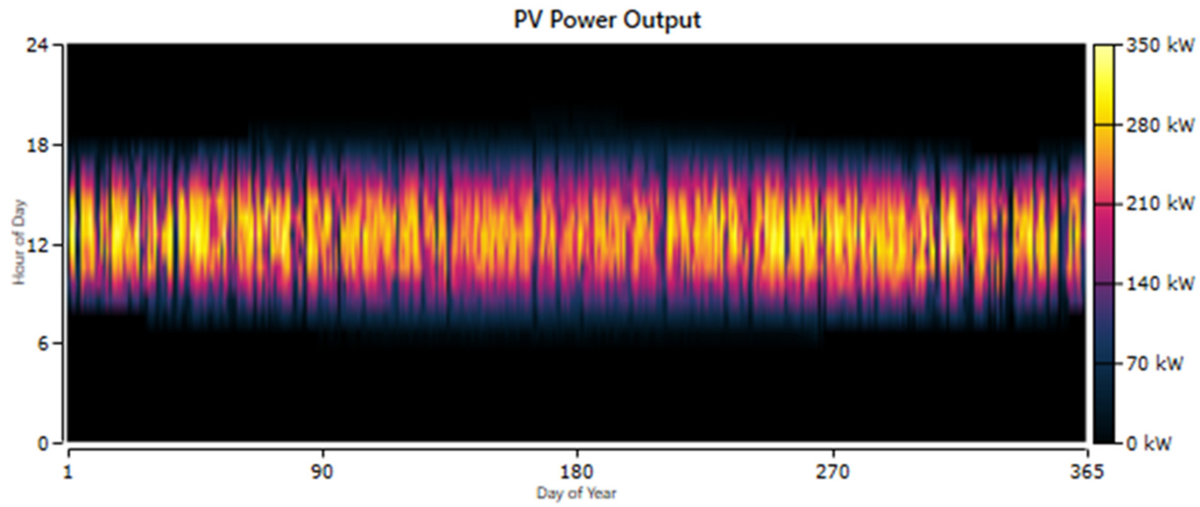

Figure 33. Electric power generation from PV during the entire year.

In [50], we generate electrical energy at a cost of \$0.0574/kWh (Rs. 8.90/kWh) using the same resources for different locations and in a grid-connected mode. The reason why this COE is lesser in this case is excess energy generation is sold back to the grid. In [51], we modeled a micro-grid scheme based on PV, diesel generator and battery backup. The COE from this system is \$0.207/kWh (Rs. 32.10/kWh). Here, COE is higher than our results because of a change in energy resources, and the location area. In [52], we designed a hybrid system using PV, biomass and micro-hydro. The COE for this system is \$0.084/kWh (Rs. 13.02/kWh) for the most feasible system.

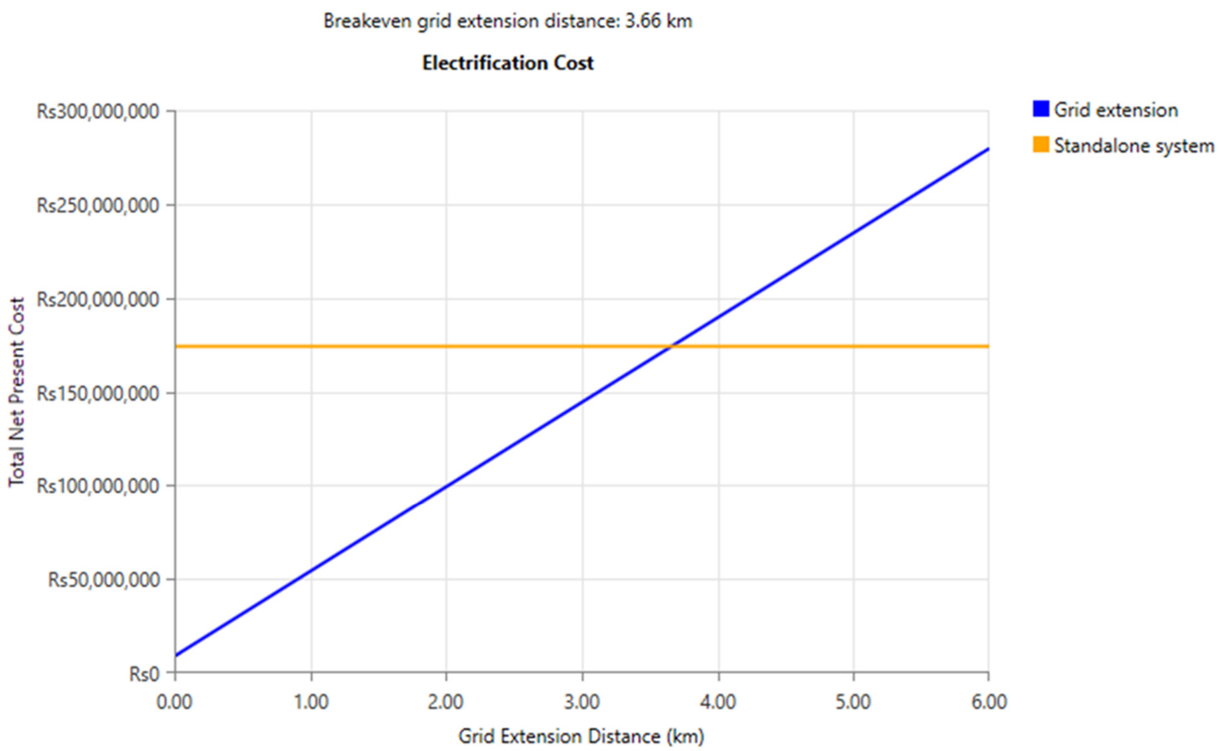

Figure 34. Grid-extension limit estimation.

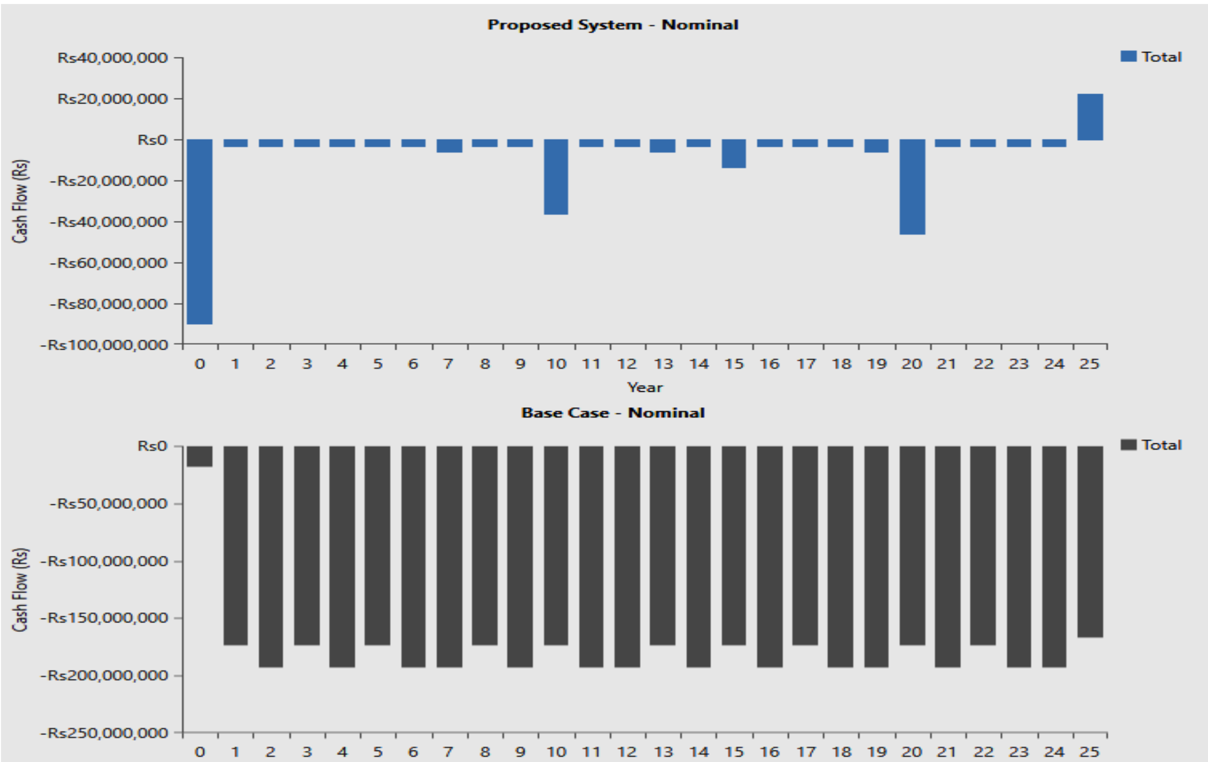

Figure 35. Cash flow comparison for Baluchistan location

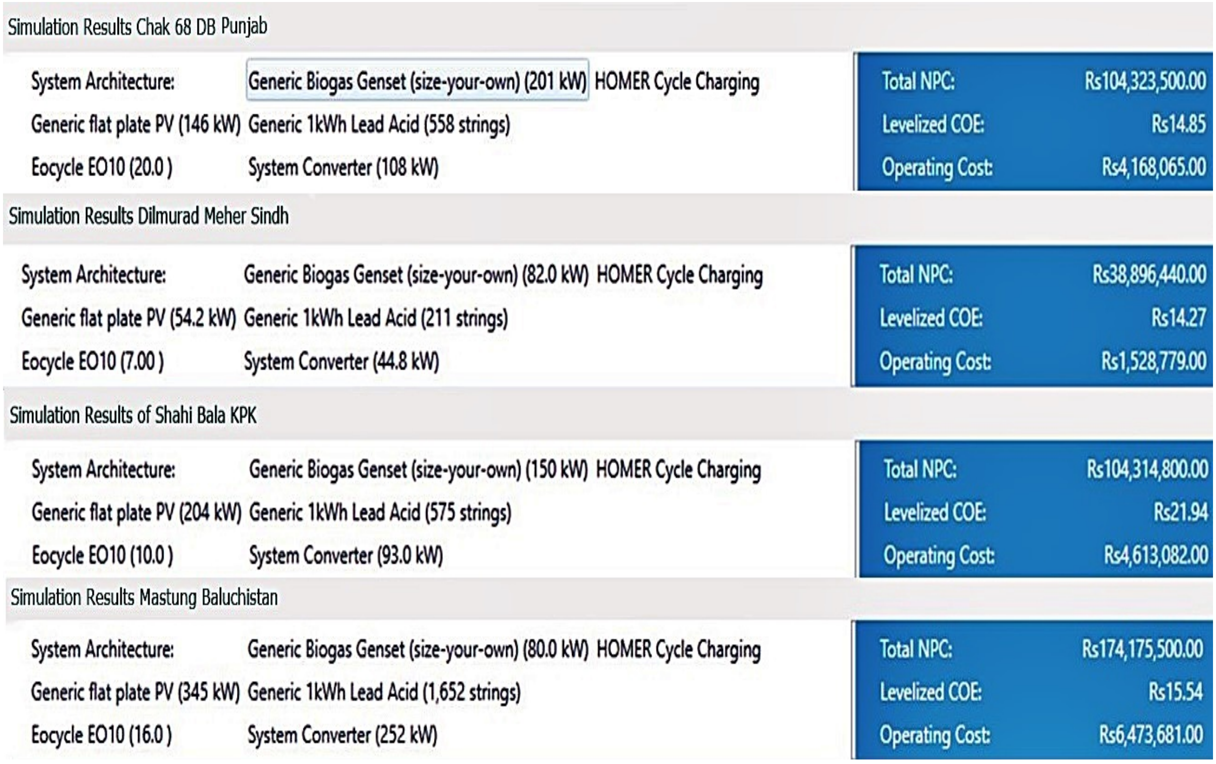

Figure 36. System Architecture and financial parameters of all four locations.

6. Conclusions

Pakistan is facing its worst energy crisis and a major dependence for electricity generation and then I should be able to make it today is on fossil fuels, which are imported. Determining the renewable energy resources across different regions of the country would help in expanding cleaner energy generation. Techno-economic analysis for areas having good solar, wind and biomass potential will attract investors to developing small power plants to fulfill local energy demands. Evolving energy systems to fulfill the energy demand while keeping the environment clean and green is extremely important at the present time.

Excess energy is generated in each hybrid technique, due to the excessive generation at the peak hours of solar and during high wind-blowing hours. This excess energy generated is a plus point; it could be sold to the nearest commercial energy consumers to generate some revenues and further lower the COE and NPC of the designed system. The minimum COE comes for the Sindh rural area whereas for KPK it is the maximum among all regions. The COE, NPC and payback period of remote locations for Punjab is 14.85 Rs/kWh, 104.32 M Rs and 3.1 years, respectively. Likewise, for Sindh, KPK and Baluchistan rural areas, we have 14.27 Rs/kWh, 38.89 M Rs and 1.9 years; 21.94 Rs, 104.31 M Rs and 2.8 years; and 15.54 Rs/kWh, 174.17 M Rs and 4.1 years, respectively.

Using biomass as an energy resource in the system increases the system's stability towards power demand fulfilling and it has no harmful effect on to the environment. Additionally, it reduces waste, which should be disposed of otherwise. The cost of generated energy is comparable to the grid electricity and ensures 24 h power supply without cut off and load shedding to the un-electrified rural area. Furthermore, slurry left in the end after biogas production from biomass waste could be sold as a high quality fertilizer to the local farmers that would also generate some revenue and bring down the overall cost of the hybrid system. This study can be a guideline and work-map for other developing countries to follow. The major challenge is scaling up of the sample size and in the future, the study will be extended to various climatic regions to access their impacts.

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