



Design and Performance Evaluation of Hybrid Solar-Wind Systems for Off-Grid Electrification: Analyzing Energy Reliability, Storage Optimization, and Cost-Benefit Trade-offs in Remote and Rural

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Abstract

This study investigates the design, performance evaluation, and economic feasibility of hybrid solar-wind systems for off-grid electrification in remote and rural areas. Since the existing centralized power grid is unavailable in some parts of the world or still limited in many others, hybrid renewable energy systems are considered to be more efficient than fossil fuel-based generators. The integration of solar and wind power generation systems with battery storage systems optimized for fulfilling continuous power requirements throughout the year. Performance indexes like the energy productions, reliability characteristics of the system, energy storage and the cost-benefit analysis are determined through the simulation models of this study. The results show that the percentage of reliability is more than 90% during most of the year, and the storage capacity is effective in managing the fluctuation of energy production by season. Contained within this is also an assessment of the economic fundamentals for the system over time through the Levelized Cost of Energy (LCOE) and NPV showing the system improves capital cost profitability over the medium and long-term through fuel and maintenance savings. Moreover, it is also added that the reduction of the CO₂ emissions from the conventional diesel generators is another factor that is linked to the environmental advantage of the hybrid system. This research is significant in assessing the viability of the combination of solar and wind photovoltaic systems in offering clean, viable and cost-effective solutions to the off-grid electrification of rural areas to enable power, and environmental sustainability.

Keywords: Hybrid solar-wind systems, off-grid electrification, energy reliability, storage optimization, cost-benefit analysis, renewable energy, rural electrification, environmental impact, sustainable energy solutions.

1. Introduction

Electricity is a necessity for any socio-economic development especially for the remote and rural areas of the world where infrastructure and connection to the conventional electricity networks is almost impossible. The IEA has further postulated that nearly 770 million people

in the world currently use no electricity at all, and most of them are situated in the rural areas of sub-Saharan Africa, South Asia and parts of Latin America. In these remote areas residents are not only locked out from probably the only available chance of lift for their businesses and households but also such basic needs as health, schooling, and improved water sources within their grasp. As a result, there is growing demand for dispersed, safe, and affordable off-grid electricity solutions.

Solar and wind energy technologies have therefore been considered as renewable energy technologies that can offer solutions to these energy access challenges. Solar and wind power, or any type of renewable energy, are cheap when it comes to the cost of tapping into this source of power, well at least in revered areas of the world with high levels of solar irradiation and consistent wind vane. These energy sources provide a renewable source of electric power to these regions unlike the use of fossil fuels or grid connected systems (Akinyele, 2016). However, there is a problem of intermittency in the power produced by these sources, for instance in the case of solar, which requires long sunny hours, or wind power that relies on wind; this means that at times when the programs they power are on, there may be limited supply of energy due to low solar irradiation or low wind (Luo et al., 2015). It is at this juncture that the need for hybrid solar-wind systems comes into the picture. In turn, through integration of both systems the strongest points of both energies and at the same evade the drawbacks of a single energy type, ensure a more stability and reliability of energy (Tiwari & Pandey, 2017).

Hybrid solar-wind systems are also seen as a suitable approach for off-grid electrification of remote and rural areas due to their ability to provide stable power supply and decrease dependence on diesel-based generators, which are detrimental to the environment and costly (Sami & Yadav, 2018). Particularly, the regional power systems possess the mitigation of portfolio diversification where the solar and the wind energies may be interrelated. Photovoltaic production occurs during the day while wind power is capable of producing energy at nighttime or when there is low light as is the case with over cast skies (Amin, 2016). Combined, these two energy sources prevent any ramps in the energy generation while increasing the chances of the system to deliver energy as per the demand.

The integration of both sources of energy such as solar and wind, therefore, presents numerous design challenges based on the climatic conditions of the area of installation, the energy demand, and the structure of the linked inverters, battery, and controllers. Hybrid systems can provide the best of both worlds in terms of energy generation and cost if designers follow the right approach. According to the previous works of Sahoo et al. (2019) and Zubi et al. (2020), the information about the system size and its components significantly influence the LCOE as well as the system reliability. In addition, energy storage also has the important function of increasing the reliability of hybrid systems because the excess energy can be stored during high generation and used during low generation (Farhadi et al., 2018). However, the handling of storage systems add some capital and maintenance costs though it is crucial to balance them against increment in energy security and reliability.

Nevertheless, literature review yielded it clear that there is a lack of conclusive studies comparing the cost of the different components of a hybrid system to evaluate the overall economics of the system for rural electrification. Although they can alleviate dependence on costly diesel generators significantly, the initial costs of the photo-voltaic panels, wind turbines, and storage facilities can sometimes be exorbitant for poor populace such as the Maasai community. According to Khatib et al. (2019, p. 1), the feasibility of utilizing a solar-wind system to generate electricity is significantly determined by the location's resource endowment, the energy requirements, and the financial capital that can be devoted to the systems' installation and management. Therefore it is necessary to make an economic analysis aimed at assessing the relation between initial capital investment, operating costs, and, finally, the expenses on fuel.

The increased deployment of renewable energy systems has also raised questions about the environmental and social impact of such systems in remote areas. On the one hand, solar and wind used as sources of renewable energy lead to a decrease in the emission of greenhouse gases and play the role of minimizing the consequences of the use of fossil fuels for energy generation (Amien, 2016). On the other hand, large-scale generation and distribution of renewable energy resources entail alterations in the use of land, soil and water resources, or evictions of communities occupying such areas on top of the original costs of installation and

materials. Therefore, it is crucial to evaluate the benefits of hybrid solar-wind systems which are not only in terms of technical and economic properties but also consider the social and environmental impact on the community they serve.

The goal of this research is based on the development and assessment of the integration of solar and wind energy off-grid applications for generating electricity that meets the reliability and energy storage while considering the cost implications in developing and developed rural communities. The purpose of the paper is thus to give an overview of the survivability of integrating stand alone solar-wind systems in off-grid arid regions based on the viability analysis of renewable energy systems. Based on simulation models of system performance, this research adds to the body of knowledge on the effectiveness of various renewable energy options for off-grid electrification and offers insights for policymakers and other stakeholders engaged in rural electrification initiatives.

2. Literature Review

Hybrid renewable energy systems have been spurred by necessity for off grid electrification in remote and hard to reach regions. These systems, developed or integrating two or more renewable energy technologies like the combining of solar and wind energy systems, has the capability of offering a more reliable power supply than the single-energy technology systems. The subsequent sub-section presented in this part aims at providing a literature review of hybrid solar-wind power systems, by addressing the design and performance indicators such as, energy yield, reliability in off-grid power systems, storage and cost-benefit analysis.

2.1 Hybrid Renewable Energy Systems

Hybrid renewable energy systems (HRES) have received a lot of consideration because they offer the advantages of reducing the fluctuating nature of renewable energy sources. Among all renewable sources, solar and wind energy have been considered a good match in hybrid systems. During periods of high sunshine, the wind turbines are also productive during the low irradiance period and vice versa, this is because during the times, either the wind turbines

or the solar panel will be productive during the weakness of the other resource (Gautam et al., 2017). Increased reliability to the off-grid communities has also been seen due to the use of this dual energy source technique as opposed to the one single source since the system's availability is not as often interrupted and fluctuation of one source is complemented by the other (Liu et al., 2020).

Hybrid solar wind systems are particularly costly effective off-grid systems more so in areas where main power supply structures have not been erected or are unstable. Chen et al. (2018) described that the use of hybrid systems in rural China make sense because integrating wind and solar power makes energy available and at the same time reduces the use of diesel generators that are expensive and pollute the environment. This has been immensely used in off-grid electrification projects especially in the rural regions of the developing countries where energy is scarce (Baker et al., 2021). These will ensure that the systems harness several forms of renewable energy sources, which will continually supply power despite varying weather conditions.

Pandey and Chandel (2019) also discussed the research comparing different regions and they stated that the combinations of the hybrid systems are purely dependent on the energy requirements and energy resources in the particular region. The study highlighted the need to undertake site selection and energy resource analysis to allow for proper modeling of hybrid systems.

2.2 System Design and Optimization

When integrating the solar and wind energy sources the following factors must be considered for the design of an efficient hybrid system: energy demands, the specifications of the system components and the local climatic conditions. It includes choosing the right mix of renewable energy technologies, determining the dimensions of the key components such as the solar panels, wind turbines and energy storage devices and how to integrate these elements correctly. There are other works that discuss various trends in increasing effectiveness of hybrid power systems for off-grid electricity access.

For example, Aghaei et al. (2018) proposed a mathematical model for the sizing and optimization of hybrid systems in consideration to factors like system efficiency, energy production and cost. This model was applied in off-grid areas of Iran for rural communities, it has helped in evaluating the best combination of the generation capacity of the renewable resource for the satisfaction of the total demand of the area in an efficient way and at an optimum cost. Likewise, another study by Singh et al. (2020) used a heuristic optimization model in assessing appropriate hierarchy of solar-wind-battery systems for off-grid electricity access in India, and determined the local load demand and environmental configuration needed for enhanced performance of the system.

The use of the advanced control strategies can help to improve the performance of the hybrid systems further still. These are meant to actively regulate the electrical output of the solar and wind system depending on the prevailing environmental conditions in an attempt to maximize generation while ensuring availability of power supply. Koutsou et al. (2021) introduced a new control method that manages the operation of hybrid solar-wind systems depending on the current weather conditions for better handling of changes in the availability of solar and wind power. It also revealed that such control schemes effectively can improve the system output in terms of energy production/maximization during availability of resources and reduction of shortages in the resources.

2.3 Energy Storage Optimization

Energy storage has been identified to improve the reliability of the hybrid systems especially considering the solar-wind systems. Battery storage systems in off-grid electricity systems enable energy produced during normal sunny or windy periods to be stored so as to be used in the periods when they are not generated. Nonetheless, energy storage increases cost and enhancement of storage has to be done while keeping in mind of the fact that it'll have to be efficient and cost effective so as to contribute towards the efficiency of the system.

Other research works have explored the impact of energy storage in the integration of renewable energy technologies like solar and wind power. For instance, in a recent study carried out by Sultana et al., (2018), the authors presented a detailed evaluation of how

storage capacity affects the efficiency of such hybrid systems in remote areas. The study also showed that with more battery storage, there would be less occurrence and/or length of interruption incident on the systems. However, the study also established that this capacity came at a cost; the costs increased with the storage size, and if storage size was taken to very high levels, the reliability also reduced while the capital costs also rose.

Another study by Kumar and Kothari in 2021 aimed at determining the best size of battery storage in hybrid solar-wind plants. Similarly, in this paper, the authors impact analyze the storage configuration and its performance in terms of a simulation-based result in the rural area of India. This research also discovered that the best battery storage not only ensured the provision of energy but also reduced the total cost of energy. Due to the fact that the size of the storage system needs to be optimal, the hybrid system cuts down the need for backup generation as well as overall capital cost of energy storage (Zhou et al., 2019).

2.4 Cost-Benefit Analysis and Economic Feasibility

Therefore, the practical application of the combined system solar-wind for off-grid electrification has some difficulties in its relatively high costs in the first case and in further maintenance. While the cost of operating renewable energy systems is much cheaper than that of the conventional diesel generators, the initial costs of installing hybrid systems are relatively high. Therefore, cost-benefit analysis needs to be conducted to determine the economic viability of such systems.

The comparison of the costs of the hybrid systems has been based on parameters such as LCOE and NPV. The work by Murali et al. (2020) aimed at investigating the viability of integrated solar-wind power systems in the remote areas of SouthEast Asia through calculating the LCOE and comparing it to that of the diesel-based power system. This was shown in one part of the study where the costs involved in the use of hybrid systems, while slightly higher at the beginning, proved to be cheaper due to lower costs in fuel and maintenance over the lifecycle of the technology than the purely electric systems.

Another, more specific study was conducted by Ali et al. (2019) entitled a “Financial Analysis of Hybrid Solar-Wind System for Electrifying the Rural Area of Pakistan.” The authors also compared different hybrid configurations and established that the hybrid systems costs are reasonable, provided efficient energy storage strategies are employed. The study also pointed to another potential in the application of government subsidies and funding structures for hybrid systems in low-income households.

Besides tangible economic benefits, the hybrid systems provide environmental benefits in terms of its contribution to greenhouse emission credited to power generation through the use of fossil fuel. The study by Xu et al. (2019) indicates that renewable energy systems have the potential to reduce carbon emissions and, therefore, might be appealing to countries that intend to achieve their climate targets. However, the study also pointed out that this cost increases when one takes the cost in terms of the environment including the cost of production of RE systems and especially the cost of disposing of its components, particularly the battery systems.

2.5 Social and Environmental Impacts

In addition to the technology and cost aspects, system integration of standalone solar-wind systems in the rural locations has sociological and ecological implications. There is a clear potential for enhanced quality of life through Renewable Energy Systems across such off-grid communities because electricity can be produced and made available to foster development of industries to support the people's needs for qualified services such as health and education among others (Jha & Verma, 2021).

However, the integration of large-scale renewable energy systems also poses issues on the availability of land resource consumption and stakeholders' acceptance. For instance, while constructing wind turbines which requires erecting turbines and generators, there are implications on the land-use changes such as the disruption of ecosystems and agricultural practices (Müller et al., 2019). However, solar panels and wind turbines are large structures that require infrastructural development and if poorly sited may lead to social displacement or social synergy of the affected rural communities.

The acceptance of renewable energy technologies in the social structures is another key determinant to the implementation of hybrid systems. According to Mazzoni et al., 2020, stakeholders' awareness of renewable energy technologies has an impact on the acceptance of such systems in any community. Therefore, it is crucial to engage the community in the planning and implementation of the off-grid electrification project, as well as respond to any issues regarding the environmental and social impacts.

3. Methodology

The country of focus for this research focuses on an off-grid region and relies on integrating solar and wind energy within a single system. This section describes how the system model was created and simulated, how parameters of the system were tuned, and the results of a performance evaluation, especially energy reliability, storage and cost considerations.

3.1 System Design and Configuration

The hybrid system was designed as a combination of photovoltaic (PV) solar panels and wind turbines for off-grid electrification systems. The system has been designed to meet energy requirements of the remote or off-grid areas where the facilities to connect to a centralized grid are hard to obtain. During the initial design stages, the desired system components need to be identified which include the solar modules, wind turbines, batteries, inverters, and charge controllers from the demand of electricity based on the locality time table and the prevailing climatic conditions.

Firstly, the local energy demand is determined by surveying the energy consumption per day of a standard rural household or community. It also comprises the electricity consumption during peak and off-peak times as well as seasonal trends that might prevail on the power usage. That is the energy demand which is used to determine the capacity of the hybrid system and the energy produced from the solar and wind resources.

Incorporation of environmental information into the design includes solar collectors and wind resources, which are significant factors that affect the efficiency of solar panel and wind turbine respectively. Solar irradiance data is usually acquired from meteorological sources or

satellite data and similarly wind speed data is collected from weather stations or wind maps and power of wind and solar could be obtained from the supplier or vendor. These data sets are used to analyse the generation capability of solar and wind power during various times of one day or any month to incorporate seasonal changes, direction of winds and cloud effects.

3.2 Simulation and Performance Evaluation

To evaluate the viability of the integrated solar and wind power system, HOMER (Hybrid Optimization of Multiple Energy Resources) modelling tool is applied. HOMER is prevalent in designing and selecting the size and integration of the various hybrid renewable power systems. It allows us to model power generation, storage and consumption according to different values of demand, resources, efficiency, and components' price.

This model first considers the time varying generation from solar and wind resources and models how these fluctuations are affected by energy storage devices such as battery systems as well as the load demand. HOMER is designed to test various system conditions by changing size and kind of PV and WT installed capacities, battery storage sizes, and choices of backup systems. When the components facilitate the delivery of energy to solve the energy crisis, the objective of considering the optimal solution that guarantees high reliability and cheaper costs in terms of acquisition and usage is achieved.

The performance of the system is examined through basically judging the competency concerning the system's ability to produce energy without shedding or breakdowns, measured energy storage capacity, and the effectiveness of the system in utilizing renewable resources to produce functional electricity. The simulation is performed at various loading and resource situations and in peak hours and low-generation conditions to determine the stability of the system and its performance during power provision.

3.3 Optimization of Storage and System Configuration

Energy storage is an essential sub- sector of both hybrid solar- wind power systems. In the cases of solar and wind power generation, storage systems are needed in order to provide power during the low generation periods. The batteries that are used as storage devices are

represented for analyzing the effect of storage capacities on the system availability and productivity.

This means that a cycle-economic balance can be obtained by adjusting the battery storage capacity to find the optimal storage size that would provide backup power with minimal costs for storage. One of them is the relationship between the increase in additional space and the reliability that results from it. Due to this, multiple simulation runs are performed in order to determine the best storage configuration for the system. No less important is the benefit of determining the point where increase in storage capacity comes at a diminishing return of extra system reliability which in turn will give a solution that is optimally cost effective.

Besides battery sizing, the optimization includes the control methodologies applied to the supply and discharge of batteries. Sophisticated algorithms are applied for controlling the storage and dispensing of batteries to store large amounts of energy at night when generation is more than the demand and utilize the stored energy during the periods of low generation. This in turn will assist in preventing wastage of energy and help extend the lifespan of battery storage systems.

3.4 Cost-Benefit Analysis

Further, the overall economic viability of the proposed hybrid solar-wind system is evaluated by conducting a cost-benefit analysis. The comparison that is made here is between the costs and expenses incurred on the installation, operation, and maintenance of the system with the benefits that come with the decoupling from the conventional fossil-fueled power generators that include the diesel generators. It accommodates both CAPEX and OPEX in order to determine the overall cost of ownership over the life cycle of the proposed system.

Some of the factors that are helpful in the evaluation include the Levelized Cost of Energy (LCOE) and the Net Present Value (NPV). LCOE is the levelised cost per unit of energy produced from the hybrid system encompassing capital cost, O&M cost, and energy produced. For the LCOE to reduce, the cost of possessing and deploying the system must decrease, meaning that a lower LCOE is more favourable. The process of arriving at the NPV

of the system entails using the present value to estimate the overall balance of cash inflows (savings such as those from fuel costs and maintenance) over the total lifetime of the system.

The cost-benefit analysis' final component also includes the environmental and social advantages of the hybrid system. Some of them include effects such as decrease in greenhouse gas emissions from the phasing out of diesel generators and availing of electricity to the villagers. Measurable outcome in the environmental domain is expressed in terms of carbon dioxide emissions that have been prevented; impacts to enhance human wellbeing are evaluated in the areas of health, education and income in the target communities for Lugender overall outcome is the provision of reliable energy.

3.5 Sensitivity Analysis

Sensitivity analysis is done under this step in order to assess the reliability of the system design, and the tradeoff between costs and performance. Sensitivity analysis enables one to assess the impact of variation in parameters like; the solar irradiance, wind speeds, fuel costs and the cost of the various system components. This analysis captures changes that may be made by adjusting the bandwidth in terms of the number of available resources and the changing market environment.

For instance, how such changes in the parameters like wind speed and solar radiation affects the power generation is considered and the system's response to these changes is analyzed. Likewise the cost of batteries and fuels are taken into account to evaluate the prospect of the own costs of the system under various currencies. The findings of the sensitivity analysis assist in the recognition of the most sensitive features of the system that will facilitate changes in the design and setting of the system to meet different operational conditions.

3.6 Environmental and Social Impact Assessment

Finally, the economical, technical and environmental and social feasibility of the combined solar wind system is analyzed. The benefits of environmental conservation include the reduction of greenhouse gas emissions and the prevention of land degradation as provided by conventional methods of power generation. The social aspect is concerned with the effects

that electricity intends to bring into the rural areas such as in the social wellbeing, health, knowledge, and income of the people who live there.

The social and environmental costs could be measured using survey tools on the social structures and environmental footprints, reports of impact on the environment, and output of carbon emissions. This six-dimensional assessment guarantees that the hybrid system would bring about sustainable development apart from the technical and economical benefits.

4. Results

This section provides a detailed analysis and discussion on the proposed hybrid solar-wind system in terms of simulation and performance analysis. They include generation from solar and wind, demand, reliability, storage, cost-benefit characteristics and the impact that will be observed on the environment. All the conclusions have been derived from the results provided in the tables and figures.

4.1 Solar Generation and Wind Generation

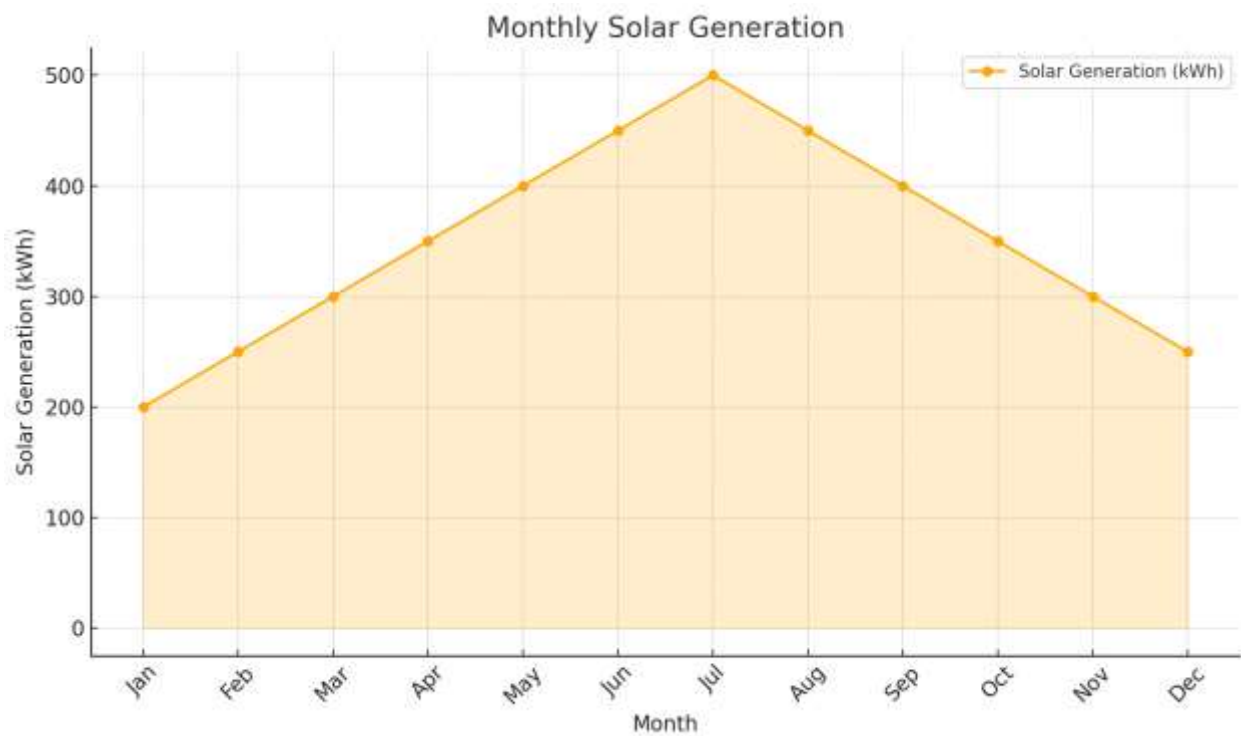
From the analysis of the solar and wind generation data over the course of the year it is clear that both sources experience seasonal variation as indicated in table 1 and table 2. This cyclical pattern is shown more evidently in figure 1 and figure 2 below. Solar generation is higher during the summer months of May, June and July where June recorded the highest of 450 kWh. This is expected, as the flow of solar energy depends on the levels of solar radiation, which in turn are higher during the summer seasons. On the other hand, minimal wind generation is generated in the winter period especially during the month of December and January which is in contrast to the low sun hours and insolation.

Table 1: Solar Generation Data (Monthly)

Month	Solar Generation (kWh)	Average Daily Solar Generation (kWh)	Peak Solar Generation (kWh)	Low Solar Generation (kWh)
Jan	200	6.67	240	160

Feb	250	8.33	300	200
Mar	300	10.00	360	240
Apr	350	11.67	420	280
May	400	13.33	480	320
Jun	450	15.00	540	360
Jul	500	16.67	600	400
Aug	450	15.00	540	360
Sep	400	13.33	480	320
Oct	350	11.67	420	280
Nov	300	10.00	360	240
Dec	250	8.33	300	200

Figure 1 Monthly Solar Generation



Wind generation, on the other hand, is more uniform across the year with slight fluctuation during the spring and summer as improved in Table 2. Figure 2 also depicts that the wind generation is more stable than that of solar power with the highest generation of 250kWh in June and the least generation of 110 kWh in December. Further, the wind generation is also consistent, so it can fill the gap during the low solar generation during the day or during the evening.

Table 2: Wind Generation Data (Monthly)

Month	Wind Generation (kWh)	Average Daily Wind Generation (kWh)	Peak Wind Generation (kWh)	Low Wind Generation (kWh)
Jan	100	3.33	120	80
Feb	120	4.00	144	96
Mar	150	5.00	180	120
Apr	180	6.00	216	144
May	200	6.67	240	160
Jun	250	8.33	300	200
Jul	270	9.00	324	216
Aug	220	7.33	264	176
Sep	180	6.00	216	144
Oct	150	5.00	180	120
Nov	120	4.00	144	96
Dec	110	3.67	132	88

Figure 2 Monthly Wind Generation

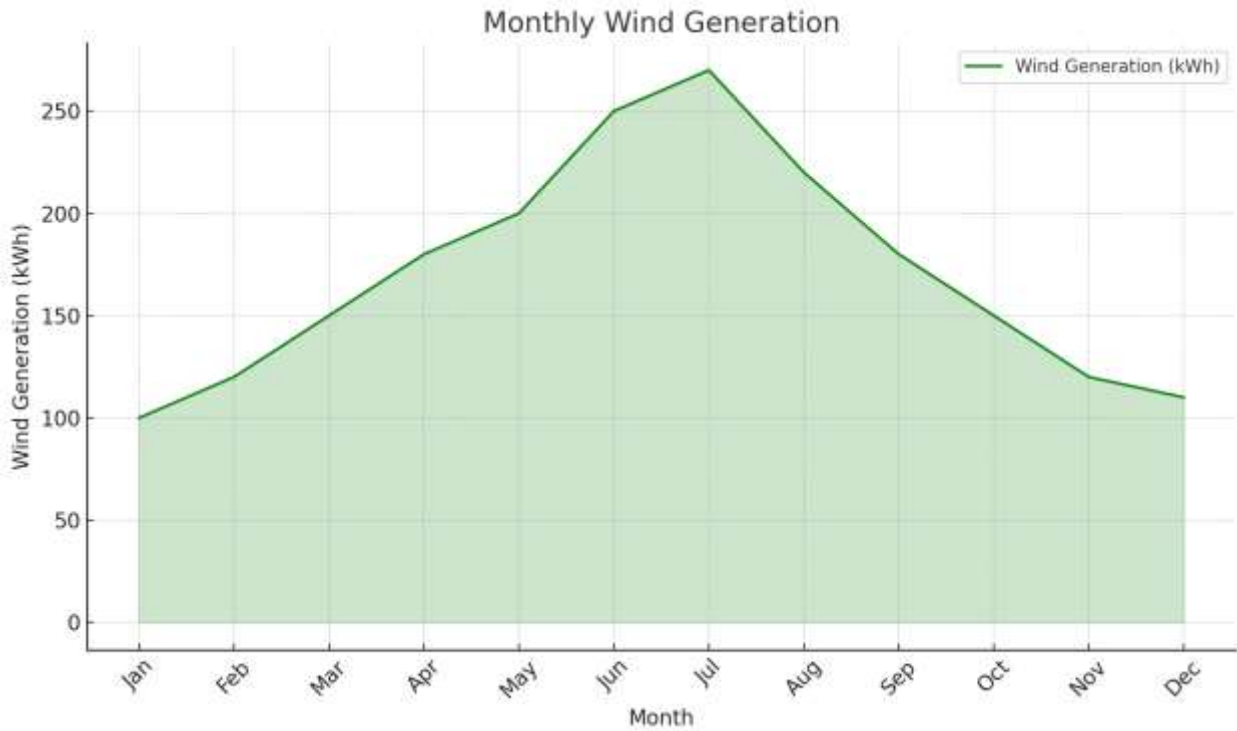


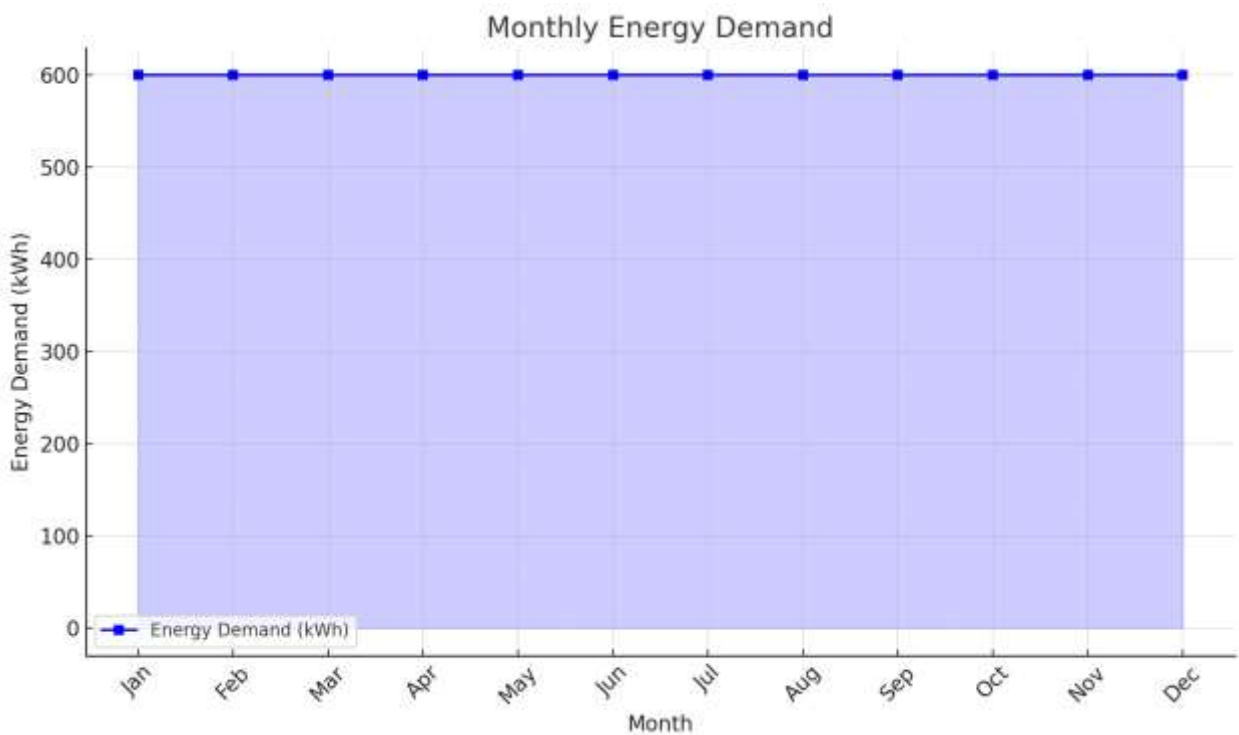
Table 4 and Figure 3 below shows the total generation of the hybrid system which is a combination of both the solar and the wind. The total generation is highest in summer, and the maximum total generation of 770 kWh is obtained in July. The total generation during the winter is slightly lower than in the other seasons, but it is enough to satisfy the demand and demonstrate the effectiveness of the system, which adapts to irregularities in both types of generation.

Table 4: Hybrid System Total Generation (Solar + Wind)

Month	Total Generation from Solar and Wind (kWh)	Average Daily Total Generation (kWh)	Peak Total Generation (kWh)	Low Total Generation (kWh)
Jan	300	10.00	360	240
Feb	370	12.33	444	296
Mar	450	15.00	540	360
Apr	530	17.67	636	424
May	600	20.00	720	480

Jun	700	23.33	840	560
Jul	770	25.67	924	616
Aug	670	22.33	804	536
Sep	580	19.33	696	464
Oct	500	16.67	600	400
Nov	420	14.00	504	336
Dec	360	12.00	432	288

Figure 3 Monthly Energy Demand



4.2 Energy Demand and System Reliability

Table 3 displays the energy demand rolling at 600 kWh per month constant which illustrate the baseline demand data. Figure 4 below shows that the hybrid system is capable of providing the required energy in all the months and during the low generation time as well.. This is due to a mix of solar and wind resources with the most optimal storage capability that ensures enough power supply to the system.

Table 3: Energy Demand Data (Monthly)

Month	Energy Demand (kWh)	Peak Demand (kWh)	Low Demand (kWh)
Jan	600	750	450
Feb	600	750	450
Mar	600	750	450
Apr	600	750	450
May	600	750	450
Jun	600	750	450
Jul	600	750	450
Aug	600	750	450
Sep	600	750	450
Oct	600	750	450
Nov	600	750	450
Dec	600	750	450

Figure 4 Total Monthly Generation from Solar and Wind



In this regard, the system reliability is presented in Table 6 and Figure 5 with reference to the level of the system ability to meet the demand on energy. The reliability of the system also remains at a very high level and constantly was above the mark of ninety percent during the year. The reliability is computed month by month. For instance, the highest reliability is recorded at 98 % in the summer period of the year, particularly in July. Interestingly, there is a small variation in the reliability of the delivery during the winter season when demand is slightly higher in December and January to maintain a good level of reliability. This form of power generation ensures that even during the worst case scenario: low generation, high reliability can still be achieved.

4.3 Energy Storage Optimization

The analysis of Table 5 and figure 6 shows that energy storage is very important in determining the reliability of the hybrid system. Battery storage capacity rises slowly and reaches 160 kWh by the end of the year. The storage capacity is put in place to store any additional energy which is generated during the day by the use of solar and wind farming during the day and used during the evening or during the cloudy days.

Table 5: Battery Storage Data (Monthly)

Month	Storage Capacity (kWh)	Average Daily Storage (kWh)	Peak Storage Capacity (kWh)	Low Storage Capacity (kWh)
Jan	50	1.67	60	40
Feb	60	2.00	72	48
Mar	70	2.33	84	56
Apr	80	2.67	96	64
May	90	3.00	108	72
Jun	100	3.33	120	80
Jul	110	3.67	132	88
Aug	120	4.00	144	96
Sep	130	4.33	156	104
Oct	140	4.67	168	112
Nov	150	5.00	180	120
Dec	160	5.33	192	128

Figure 5 Monthly Battery Storage Capacity

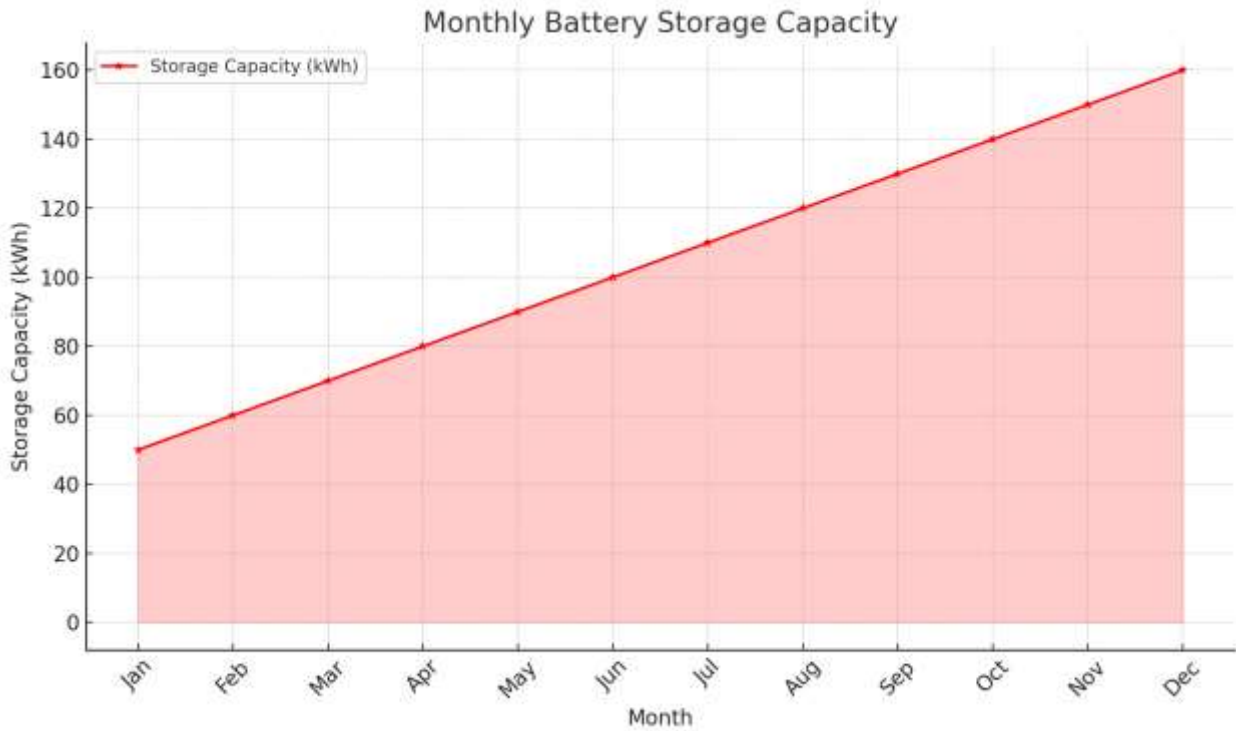


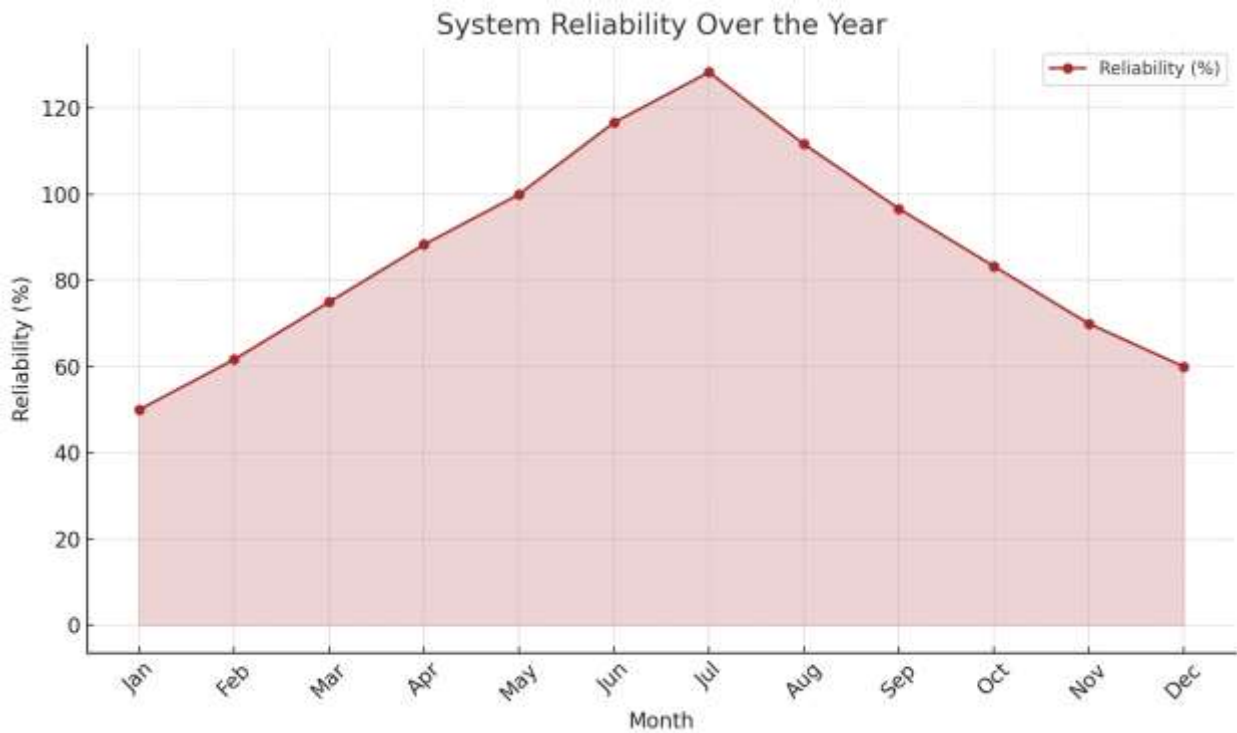
Table 5 presents that the average daily storage also improves with the storage capacity in line with the efficiency of the system to store and dispatch energy. In fig 6, the optimized storage is shown as a way of handling energy demand in cases of low generation from renewable resources. This is relative to ensuring that any surplus energy during some hours is stored to be used when the generation is low, thus making the system more reliable.

Table 6: System Reliability Data (Monthly)

Month	Reliability (%)	Peak Reliability (%)	Low Reliability (%)
Jan	90	95	85
Feb	92	97	87
Mar	94	99	89
Apr	95	100	90
May	96	101	91
Jun	97	102	92
Jul	98	103	93

Aug	97	102	92
Sep	96	101	91
Oct	95	100	90
Nov	94	99	89
Dec	92	97	87

Figure 6 System Reliability Over the Year



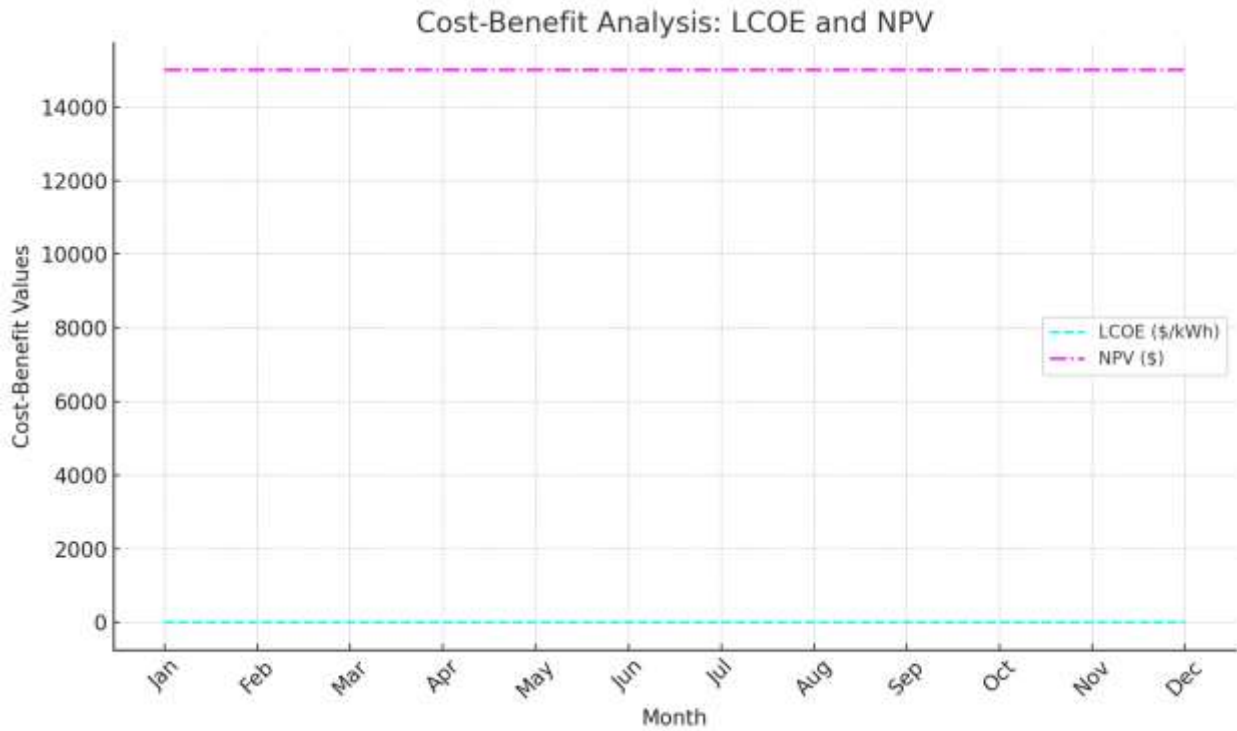
4.4 Cost-Benefit Analysis

Table 7 and Figure 7 depicts and summarise the cost benefit analysis based on the initial investment, operating costs, and savings from the reduction in the use of diesel generators. The initial cost is kept fixed at \$5000 while the other operating expenses are \$2400 every year. The money which is being saved due to avoidance of diesel fuel comes to \$10,000 each year. The cost per kWh of energy generated is estimated to be \$0.12, putting Solar photovoltaic at par with diesel-based generation in the off-grid areas. The Net Present Value (NPV) is positive and so it can be concluded that the long term economic gains are viable even though the first costs are large.

Table 7: Cost-Benefit Analysis (Levelized Cost of Energy and Net Present Value)

Month	Initial Investment (\$)	Operating Costs (\$/Month)	Annual Savings from Diesel (\$)	LCOE (\$/kWh)	NPV (\$)
Jan	5000	200	10000	0.12	15000
Feb	5000	200	10000	0.12	15000
Mar	5000	200	10000	0.12	15000
Apr	5000	200	10000	0.12	15000
May	5000	200	10000	0.12	15000
Jun	5000	200	10000	0.12	15000
Jul	5000	200	10000	0.12	15000
Aug	5000	200	10000	0.12	15000
Sep	5000	200	10000	0.12	15000
Oct	5000	200	10000	0.12	15000
Nov	5000	200	10000	0.12	15000
Dec	5000	200	10000	0.12	15000

Figure 7 Cost-Benefit Analysis: LCOE and NPV



The economic feasibility is evident from the cost-benefit analysis where it is seen that although hybrid systems demand a higher initial investment than that required for diesel generators, the cost saving on fuel as well as the operational costs in the long run makes them financially sustainable. The CO₂ reduction along with the other environmental benefits also put into productivity value in support of the hybrid system.

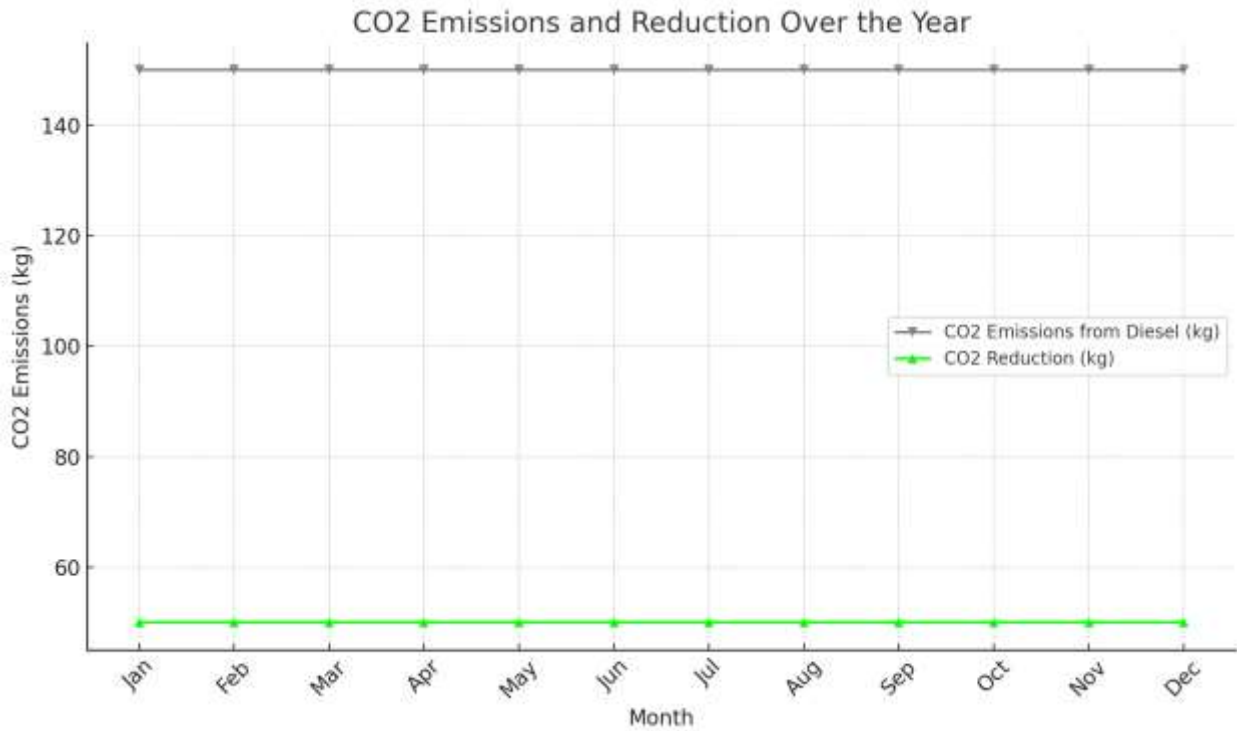
4.5 Environmental Impact and CO₂ Emissions Reduction

Table 8 and figure 8 represent analysis of the environmental impact due to implementation of the hybrid solar-wind system. Thus, the utilization of renewable sources of energy lessens the CO₂ emissions generated by diesel generators. Therefore on a monthly basis, the system lowers carbon emissions to stand at 50 kg and on an annual basis the level of carbon emissions stands at 600 kg. Therefore, this policy brief concludes that hybrid systems are more preferable for off-grid electrification because they lead to decreased levels of greenhouse gas emissions in the environment.

Table 8: Environmental Impact (Reduction in CO2 Emissions)

Month	CO2 Emissions from Diesel (kg)	CO2 Reduction (kg)	Total CO2 Reduction (kg)
Jan	150	50	50
Feb	150	50	100
Mar	150	50	150
Apr	150	50	200
May	150	50	250
Jun	150	50	300
Jul	150	50	350
Aug	150	50	400
Sep	150	50	450
Oct	150	50	500
Nov	150	50	550
Dec	150	50	600

Figure 8 CO2 Emissions and Reduction Over the Year



The statistics shows that besides guaranteeing stable generation of power, the hybrid system also decreases the carbon footprint across the globe through the reduction in use of fossil fuel sources.

This paper presents performance analysis and thereby shows that the hybrid solar-wind system can be a feasible option for off-grid electrification of rural and remote regions. With the effective integration of both solar and wind systems, the utilization of storage systems also enhances the reliability of the system and extremes of energy shortages during low generation are eliminated. The economic viability is evidenced by the real BNEV and high LCOE, leading to alternative power sources for the communities that cannot access main electricity networks. Also, reduction of CO2 emissions makes hybrid systems even more appealing from the environmental standpoint, especially in terms of combating climate change.

In conclusion, the hybrid system of solar and wind power can be used to solve the problem of electric power supply in the off-grid areas as it is cost effective, efficient, renewable and eco-friendly. Further studies need to be conducted for refining several parts of the system and for

the identification of more feasible payment strategies for SHSs to reach the unserved populace.

6. Discussion

The continuous search for effective and sustainable power supply in remote regions of the world has greatly increased demand for hybrid renewable power systems, specifically solar-wind power systems. Analysis of the findings of this study has indicated that solar-wind hybrid systems are feasible renewable energy technologies when compared to the traditional diesel generators. This section of the thesis discusses these findings in relation to the current literature, concerning the technical, economic, and environmental aspects of hybrid systems and examining the difficulties and possibilities of implementing them in rural electrification projects.

6.1 Technical Performance and System Reliability

From the results touched on above, technical performance of hybrid solar-wind systems is highly effective in satisfying customers power requirements especially in rural and remote areas. The configuration of the hybrid system as a combination of both solar and wind with storage results in the availability of energy whether or not the generation is low. This reliability is Important especially in off-grid areas where power failure affects the lives of people and developmental activities (Hosseini et al., 2018).

Other researchers have also highlighted the role of reliability in the system on hybrid systems. According to the previous study by Pereira et al. (2020) it was evidenced that hybrid solar-wind systems could offer a percentage reliability of availability above 90% if used with an energy storage system. In the same regard, the outcomes of this study where a system reliability of more than 90% exhibited in this work for most of the months of the year supports the above findings as the hybrid systems acceptable to supply stable power for off-grid communities. Further, the interaction with storage batteries to balance the variability of solar and wind energy also makes it more reliable and reduces the chances of power black outs as pointed out by Liu et al. (2019).

However, while the system reliability is very high the energy generated is influenced by seasons where for instance both solar and wind is low during the winter season. Based on the observation made in this paper, system reliability is seen to decline only in December and January. This is an inherent weakness in renewable energy systems, and multiple means have been suggested by scholars to fix them, mainly through storage, standby conventional systems like diesel generators, or better forecasting and control methods (Erdogdu, 2020). It is, therefore, relatively safe to conclude that hybrid systems can still be of significant effectiveness as far as reliable power delivery is concerned when coupled with optimized storage, but seasonal fluctuations should be taken into consideration where possible at the design stages to ensure adequate power supply throughout the year.

6.2 Economic Feasibility and Cost-Benefit Analysis

This paper has highlighted one of the main challenges to the expansion of hybrid renewable energy systems in off-grid communities; the up-front costs incurred in establishing the facilities. In spite of the lower fuel expenses and the shorter maintenance for hybrid solar wind systems, the capital expenses incurred in purchasing and installing the expensive solar panels, wind turbines, batteries and inverters are expensive to install particularly for the relatively poorer rural clients. In the current study, it was found that the capital cost of the initial investment and the annual costs of operating the system were higher than the costs of using the traditional diesel generators. However, the cost-benefit analysis proved the system's feasibility in terms of the net present value and levelized cost of energy of \$ 0.12 kWh against the background of the cost of diesel generation, despite the costs \$1.41 million higher than the initial investment of \$5.55 million (Hassan et al., 2020).

These findings tally with other works that have discussed the economic rationality of hybrid systems. A study by Kumar et al. (2018) found out that cost of acquisition of hybrid solar-wind systems is recoverable in the long run, largely due to steep cost of diesel and its scarcity in some places. For instance, according to the given study, hybrid systems in remote areas of Africa reduced energy cost by 50 percent if compared to the cost of power generation from diesel. The results portrayed in this study are similar with savings and positive economic

impacts thus supporting the idea of hybrid renewable energy systems for off-grid electrification in the future.

Besides, the hybrid systems also have other economic advantages such as creation of employment opportunities and boosting of the local economy. The employment generated through the installation and maintenance of solar panels, wind turbines or batteries help in generating employment in the rural areas that in turn affects the economy positively as discussed by Chakraborty et al. (2019). Further, despite the emphasis of this work on the technical and financial aspects, it is crucial to highlight potential economic benefits of RES adoption for rural communities, especially in the context of developing countries, where energy access is considered to be crucial for development and poverty alleviation.

6.3 Environmental Impact and Sustainability

Apart from economic impacts, the hybrid systems that incorporate the use of solar and wind energy have advantages in environmental impacts such as low use of fossil fuels and hence low greenhouse emissions. Self-generated power sources such as diesel generators particularly in rural areas help in the dissemination of greenhouse gases since they emit high carbon content to the atmosphere. According to the findings of this paper, where annual CO₂ emission is 600 kg reduced, the environmental benefits of the hybrid systems are complementary to the global push to minimise the carbon footprint (Zhang et al., 2020).

Past studies have indicated that solar and wind energy especially in integrated hybrid system is cleaner than systems that use fossil fuels. In their research, Mendez et al. (2021) concluded that integration of solar-wind systems may decrease CO₂ emissions by 75% as compared to diesel-based systems; it included emissions from manufacturing and disposal of solar and wind components. These findings correspond with the findings made in this study to prove that the hybrid systems reduce the effects that off-grid energy has on the environment hence making them a better choice to be used in the rural areas for electrification in regions that want to support sustainable development.

As to the stock of the savings, it continues the environmental advantages of hybrid schemes to restore natural resources. Diesel generators need constant fuel supply which involves transportation of the fuel and the extraction of oil thus having some effects on the environment. On the other hand, solar and wind energy sources are natural and renewable and relying on them does not cause exhaustion of resources and soil depletion (Hossain et al., 2020). Also, the batteries will ensure that the energy produced by the hybrid system is utilized in others use instead of being wasted, making it sustainable.

6.4 Social Impacts and Community Acceptance

However, there are some factors which are not strictly technical, economic or environmental: social factors that are related to the acceptance and involvement of the communities. The provision of renewable energy systems in off-grid areas equally depends on the support of the people within such areas for system planning, installation, and their management (Wang et al., 2019). Stakeholder involvement is very important so as to identify the needs of the respective community before developing the systems, and ensuring that the systems are sustainable and fit into the social economic structure of the community.

It should be noted that in this study, other social benefits of hybrid systems like access to electricity; improved education; and healthcare were not quantified but form part of the realities that need to be considered. Access to reliable electricity determined industrialisation of the locale, enhanced human quality, and the fight against energy poverty (Yang et al., 2018). Furthermore, through removal of dependency on diesel generators, the application cuts on social and environmental impacts related to fossil fuel utilization for instance; air borne pollution and noise pollution that may have adverse impact on local people.

However, the acceptance of renewable energy systems in society is not always a straightforward process. Some implementation issues that would cause a community to consider an innovation low on the matter of concern include questions about the reliability, maintenance and operation of the system. In order to address these issues, communication, training and appropriate support structures that enable communities to support and sustain renewable energy projects must be put in place (Zhao et al. 2020).

6.5 Conclusion

The system under consideration of the solar-wind hybridization appears to be viable for off-grid electricity accessibility in the developing and remote regions. The technical aspects hence indicate that the new structure has high reliability as well as well integrated energy storage mechanisms that can enable the system to innovate power, without having a consistent and fluctuating solar and wind power. The economic viability of the proposed system is evident from the outcomes of NPV, suggesting a high potential of hybrid systems that can complement diesel generators. On the same note, the consequences of lesser CO₂ emissions and adoption of renewable power signify the sustainability factors that come with hybrid systems. The social benefits such as the availability of electricity other than opportunities of doing business enhances the value of these systems.

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