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# Numerical Study of a Hybrid System of Solar Panels, a Diesel Generator, and a Wind Turbine using a Battery System

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### ABSTRACT

This paper gives an overall quantitative analysis of a hybrid renewable energy system (HRES) incorporating solar photovoltaic system, wind system, diesel generator and battery storage system. The system is aimed at coordination the management of the energy resources for providing the off-grid or remote facilities. The best intervention is thus to increase the consumption of renewable energy sources to minimize the reliance on diesel generators. The findings show that the hybrid system is capable of supplying different levels of power, which is pumped from the solar PV panels at maximum of 30.38 kW for the photovoltaic system at maximum solar intensity, and the wind power system to a maximum of 3213 kW of power generation under standard wind potential. The diesel generator serves a backup power source, which ranges from 91.24 kW and 864 at a rate of 250 kW during high activity and 5 kW during high-demand periods. Battery storage integration has a crucial part in matching the short-term supply-demand imbalance problem. The study suggests improves energy sustainability making the system a worthy proposition for remote areas. The findings therefore affirm the use of hybrid systems in off grid electrification since they operate economically and are eco-friendly. The primary contribution of this research is the development of a model that integrates solar, wind, and battery systems into a diesel-powered grid, allowing for improved energy sustainability and cost-efficiency. The proposed system's performance is analyzed under various conditions, revealing its capability to reduce diesel consumption by up to 60%, significantly lower operational costs, and decrease carbon emissions. Through this model, renewable energy sources, specifically solar and wind, can supply a significant portion of the total energy demand, with the diesel generator functioning as a supplementary source.

## 1. Introduction

The shift to sustainable energy solutions has brought about significant studies into hybrid renewable energy systems (HRES) which integrate solar photovoltaic (PV), wind turbines, diesel generators, and batteries. These systems are identified as the best for increasing the use

of renewables, guarantee reliability and minimize impacts caused by conventional power generation fueled by fossil resources. This paper presents an analysis of the literature in the areas of HRES planning, design and optimization as well as its application.

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Some researches dealt with the layout and design of the solar photovoltaic systems incorporating wind power, diesel engine generators, and batteries aiming at providing reliable energy sources for off-grid or dramatically remote sites. Li et al. (2017) [1] discussed an HRES model concerning with renewable energy and conventional diesel to provide the electricity load. The study focused on the application of energy storage system in improving system integrity and performance of the system under varying renewable energy supply conditions. In another work, Khalid and Ahmed (2020) [2] further compared the various possibilities of the hybrid systems with emphasis on the solar-Wind-Diesel. According to their research, they discovered that it was possible to minimize the use of diesel generators for energy by incorporating battery storage that would further reduce on fuel usage and cost of doing so. All these studies point towards the increasing necessity for bringing energy storage systems into hybrid configurations. Another area of significant concern in current research is the management of energy within the systems where hybrid configurations have been adopted; several papers have put forward sophisticated control strategies to control distribution of power and hence improve on the performance of the systems. Chen et al. (2018) [3] presented the control strategy for a solar-wind-diesel-battery system where battery system is used to store energy to meet the demand in the absence of solar and wind energy. Finally, they pointed out that the amount of charging and discharging cycles of the battery should be controlled in order to maximise the life of the system. Sinha and Chandel (2021)[4] presented an optimization model for scheduling hybrid renewable system against fuel and, by employing demand-side management strategies, optimal utilization of renewable resources. Using the findings from their work, they showed that proper coordination of solar, wind and diesel power

can lead to significant enhancement of system efficiency and decrease of carbon footprint.

Hitherto a lot of focus has been given to researching about the economic feasibility of HRES. HOMER Energy is one of the powerful modeling tools that is used generally for simulating the efficiency of hybrid system based on the variations in climatic conditions and cost. In their study using techno-economic analysis of solar-wind-diesel hybrid systems, Shahzad et al. (2019) [5] observed that inclusion of battery storage greatly reduce the LCOE. The effectiveness of such a design proves the increasing application of the integrated systems in the distant and rural areas which are often undersupplied with the grids or require the expensive power supply. In addition, Khan et al. (2020) [6] investigated into payback period and ROI of hybrid renewable systems with battery storage and observed that subsidies towards renewable energy by the government and decline in battery prices enhance the prospect of economic feasibility of those systems. Another reason for hybrid renewable systems is that carbon footprints by power generation are also a matter of grave concern. Research by other scholars including Akinyele et al (2018)[7], proved that it is possible to reduce GHG emissions when solar and wind system are combined and heavily relying on diesel generators. They have concluded that hybrid systems are more sustainable than diesel-only power systems despite the current dominant use of fossil fuel especially in remote and island states. Furthermore, Dursun and Gokcol (2021) [8] added that systems with high proportion of renewables and batteries eliminate not only fuel consumption but also reduction in maintenance cost of diesel generators which is yet another factor relevant to environmental sustainability.

The following are case studies showing the practicalities and real life experiences of the

challenges as well as achievements of implementing HRES. Elhadidy and Shaahid (2020) [9] investigated the application of hybrid solar wind diesel system for supplying electricity to rural Saudi Arabian villages. This finding thereby revealed that with battery storage as means to store power generated and utilizable at other times, the dependence on diesel generators was minimized which gave off a clean and constant supply of electricity. Similarly, Zhang et al. [10] have recently studied the feasibility of utilizing solar-wind-diesel integrated system for microgrid application in china. One of the key observations made in the study is that energy storage is central to the goal of achieving energy independence and maintaining structure of the grid particularly during the fluctuating renewable energy reliance. As pointed out by Liu et al. (2019) [11], Li-ion batteries that are different from traditional lead-acid batteries have been shown to be more suitable in the operation of HRES especially where cycling in the system is frequently as is the case of solar and wind energy. The authors underline that Battery Management Systems (BMS) are responsible for controlling and providing safety of battery operation by managing temperature, voltage and State of Charge (SOC). Some of the other reviews that have been carried out on the potentials of new battery chemistries include Gautam et al. (2020) [12] and the ability to use solid-state batteries and flow batteries for HRES. Compared with the conventional lithium-ion batteries, solid-state batteries have higher energy densities and enhanced security performances; as for the flow batteries, like vanadium redox flow batteries, they have well-developed deep discharge cycles and relatively lower capacity attenuation.

El-Shimy (2020) [13] put together a model that provides a measure of the generation of solar radiation and the power characteristics of solar panel and wind turbines. The study also

showed how predictive modeling could be employed to approximate energy production and also charge/ discharge the batteries in an appropriate manner, hence increasing system efficiency and decreasing fuel usage. In the same year, Salama et al. (2021) [14] applied artificial intelligence (AI) including artificial neural networks (ANN) to forecast energy demand and generation in hybrid system. Due to this variability of renewable power sources, AI-based models have been pinpointed as remarkably useful to enable real-time management of the performance of the system. This year, Ravi & Singh [15] employed RL in order to improve the control strategy of a solar-wind-diesel-battery micro-grid. It helped them to influence the system's and identify the best strategies for dispatching the power based on historical data and the current situation. The RL algorithm enhances the use of batteries' usage, cuts down on fuel, and increases the life cycle of the system due to load sharing between renewable resources and a diesel generator. Another study done by Ahmed et al. (2022) [16] developed a machine learning prediction system for maintenance of HRES. In this way, with the help of the determined ML algorithms, the system could predict the manifestation of signs of battery degradation or elements' failure, which would otherwise lead to high maintenance expenses and the stoppage of the system's operation.

### Research Gaps:

1. **Dynamic Energy Management:** Current studies lack comprehensive models that dynamically balance energy generation from renewable sources with battery storage and diesel generators. Research has predominantly explored static systems that are less adaptable to fluctuations in energy production and demand.
2. **Cost and Environmental Impact:** While the economic and environmental

advantages of renewable energy integration have been acknowledged, detailed analyses quantifying diesel savings and emission reductions in hybrid systems are still sparse.

3. **System Scalability and Versatility:** There is limited work on how HRES can be adapted for various industrial applications, such as telecommunications, mining, and disaster relief, where reliability and sustainability are crucial.

**Objective and Uniqueness of the Study:**

This research aims to address these gaps by proposing a dynamically controlled HRES that integrates solar PV, wind energy, diesel generators, and advanced battery storage. A unique aspect of the study is the introduction of an energy management algorithm that optimizes the distribution of power among these resources, ensuring maximum efficiency while reducing diesel consumption and environmental impact.

The objective of this work is to design a hybrid renewable energy system consisting of solar PV, wind energy, diesel generator and energy storage system for numerical analysis. The primary objective, therefore, is to apply best practices to assess the best option for controlling energy especially in regions whereby power is unavailable or hard to come by. With the assistance of renewable energy in the form of solar and wind, the system try to reduce dependence on diesel generators.

**2. Methodology**

There is also a Simulink simulation of a hybrid renewable system of solar PV, Wind, DG, and Battery storage for the assessment of system performance in various conditions. Firstly, a block diagram of each of the components is made using Simulink Power Systems library and the resources available

from MATLAB: The solar PV, wind turbines, diesel generator and battery block represents the energy storage system. In the control strategies, there is provision to give priority to renewable resources; the diesel generator is provided to standby. The energy management algorithm controls the charging and discharging of the battery with regards to load demand as well as available renewable generation. Situations like high sun or wind energy and low renewable power generation are again modeled to know how the system fulfills the demand. The outcomes encompass generation of electrical power, battery SoC, and diesel fuel consumption to enhance the system’s performance for productivity and decrease fuel consumption level for environmental safety concerns. This has made it possible to fine-tune control schemes and system interfaces for making the best use of renewable energy resources while making a least impact on the environment.

*2.1 PV panel*

The Photovoltaic (PV) panel equations model the conversion of solar irradiance into electrical power. The following are the key equations that describe the operation of a PV cell, which are often used in simulations and analyses.

1 PV Cell Output Current Equation:

The output current of a PV cell  $I_{PV}$  is expressed as [17]:

$$I_{PV} = I_{ph} - I_d - I_{sh} \tag{1}$$

2 Photocurrent  $I_{ph}$  :

The photocurrent is directly proportional to solar irradiance and temperature [18]:

$$I_{ph} = [I_{ph,ref} + k_I(T_c - T_{ref})] \times \frac{G}{G_{ref}} \tag{2}$$

3 Diode Current  $I_d$  :

The diode current describes the current flowing through the PN junction and follows the Shockley diode equation [19]:

$$I_d = I_0 \left( e^{\frac{V_{PV} I_{PV} R_d}{nV_T}} - 1 \right) \quad (3)$$

4 Shunt Current  $I_{sh}$  :

The shunt current is caused by the shunt resistance  $R_{sh}$  of the cell [20]:

$$I_{sh} = \frac{V_{PV} + I_{PV} R_s}{R_{sh}} \quad (4)$$

5 PV Panel Power Output:

The power output  $P_{PV}$  of a PV panel can be calculated by:

$$P_{PV} = V_{PV} \times I_{PV} \quad (5)$$

6 Effect of Temperature on Voltage:

The open-circuit voltage  $V_{oc}$  decreases with an increase in temperature [21]:

$$V_{oc}(T_c) = V_{oc,ref} - k_V(T_c - T_{ref}) \quad (6)$$

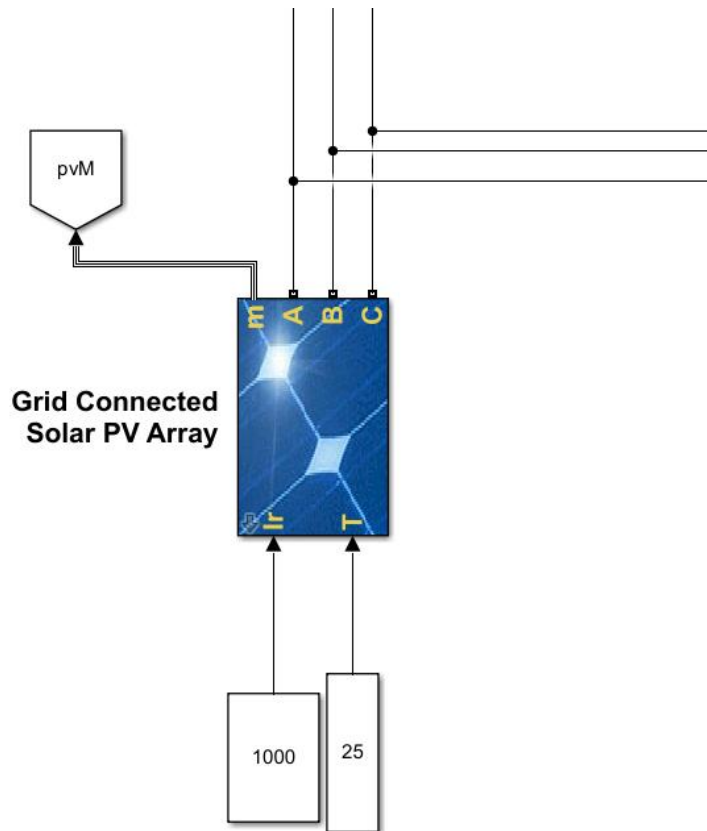


Figure (1): PV system in Simulink

2.2 Wind turbine

The performance of a wind turbine can be modelled using several key equations that

relate wind speed, turbine dimensions, and power output. Below are the important equations used to describe the energy conversion process in wind turbines.

### 1 Power Extracted from the Wind:

The power extracted by a wind turbine from the wind is given by the following equation [22]:

$$P_{\text{wind}} = \frac{1}{2} \rho A v^3 C_p \quad (7)$$

### 2 Swept Area:

The swept area  $A$  of the turbine blades is the area through which the wind passes, and is calculated as [27]:

$$A = \pi r^2 \quad (8)$$

### 3 Tip Speed Ratio (TSR):

The Tip Speed Ratio (TSR) is a dimensionless number that represents the ratio between the blade tip speed and the wind speed [23]:

$$\lambda = \frac{\omega r}{v} \quad (9)$$

### 4 Power Coefficient ( $C_p$ ):

The power coefficient  $C_p$  is the efficiency with which the turbine converts the kinetic energy of the wind into mechanical power. The power coefficient depends on the tip speed ratio  $\lambda$  and the pitch angle of the blades  $\beta$ . A common empirical equation to approximate  $C_p$  is [24]:

$$C_p(\lambda, \beta) = 0.22 \left( \frac{116}{\lambda_i} - 0.4\beta - 5 \right) e^{\frac{1225}{\lambda_i}} \quad (10)$$

### 5 Mechanical Power:

The mechanical power produced by the turbine is the power from the wind reduced by the power coefficient:

$$P_{\text{mech}} = P_{\text{wind}} \times C_p \quad (11)$$

### 6 Torque Produced by the Wind Turbine:

The mechanical torque  $T$  produced by the turbine is related to the mechanical power [30]:

$$T = \frac{P_{\text{mech}}}{\omega} \quad (12)$$

### 7 Betz Limit:

The Betz Limit states that the maximum possible efficiency for converting wind energy into mechanical energy by a wind turbine is approximately 59.3%, or  $C_p = 0.593$ . This can be expressed as:

$$C_p \leq 0.593$$

### 8 Wind Power Density:

The wind power density, which measures the available power per unit area, is calculated by:

$$P_{\text{density}} = \frac{1}{2} \rho v^3 \quad (13)$$

### 9 Efficiency of the System:

The overall efficiency  $\eta$  of the wind turbine system, taking into account the gearbox, generator, and other mechanical losses, can be expressed as:

$$\eta = \eta_{\text{gearbox}} \times \eta_{\text{generator}} \times C_p \quad (14)$$

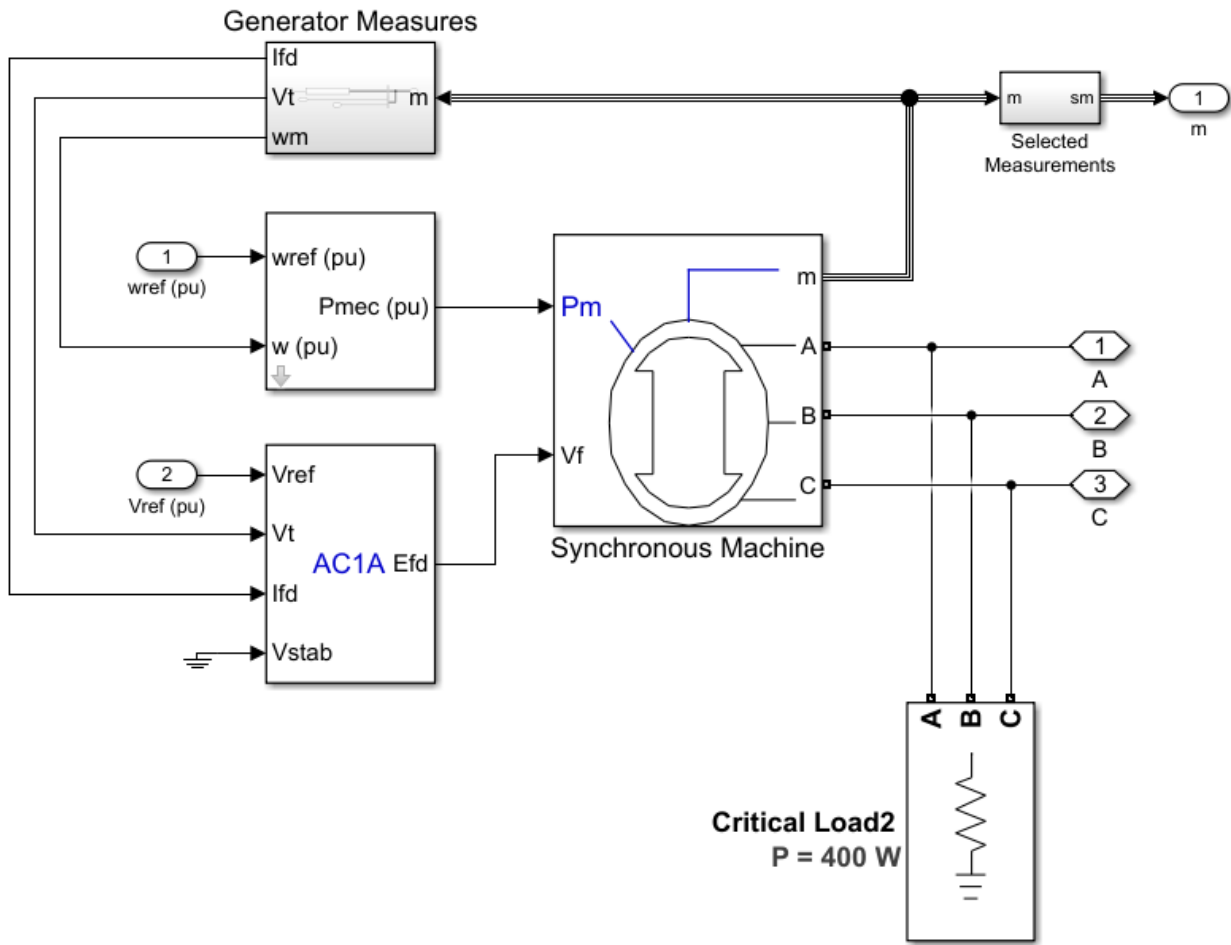


Figure (2): Wind turbine system in Simulink

### 2.3 Diesel generator

A diesel generator converts the chemical energy of diesel fuel into electrical energy through combustion and mechanical work. The following are key equations that describe the performance, fuel consumption, efficiency, and power output of a diesel generator.

#### 1 Power Output Equation:

The mechanical power output of a diesel generator can be expressed as [25]:

$$P_{\text{mech}} = T \cdot \omega \quad (15)$$

For electrical power output, the mechanical power is converted, taking into account the efficiency of the generator:

$$P_{\text{elec}} = \eta_{\text{gen}} \cdot P_{\text{mech}} \quad (16)$$

#### 2 Fuel Consumption Rate:

The fuel consumption of a diesel generator is generally proportional to the electrical power output. A common formula to estimate fuel consumption in liters per hour (L/hr) is [26]:

$$F_{\text{rate}} = \frac{P_{\text{elec}}}{\eta_{\text{gen}} \cdot \eta_{\text{engine}} \cdot H_{\text{diesel}}} \quad (17)$$

### 3 Specific Fuel Consumption (SFC):

The specific fuel consumption (SFC) measures the efficiency of the generator, indicating how much fuel is consumed per kWh of energy produced:

$$SFC = \frac{F_{rate}}{P_{elec}} \quad (18)$$

### 4 Heat Energy of Diesel Fuel:

The total heat energy produced by the diesel fuel during combustion can be calculated by [33]:

$$Q_{fuel} = \dot{m}_{fuel} \cdot H_{diesel} \quad (19)$$

### 5 Thermal Efficiency of Diesel Generator:

The thermal efficiency of a diesel generator is the ratio of the useful mechanical power output to the total fuel energy input:

$$\eta_{thermal} = \frac{P_{mech}}{Q_{fuel}} \quad (20)$$

### 6 Electrical Efficiency:

The overall electrical efficiency  $\eta_{elec}$  of the diesel generator is the product of the thermal efficiency and the generator efficiency [27]:

$$\eta_{elec} = \eta_{thermal} \cdot \eta_{gen} \quad (21)$$

### 7 Air-to-Fuel Ratio (AFR):

The air-to-fuel ratio is a crucial parameter for combustion efficiency, indicating how much air is supplied relative to the amount of fuel [28]:

$$AFR = \frac{m_{air}}{m_{fuel}} \quad (22)$$

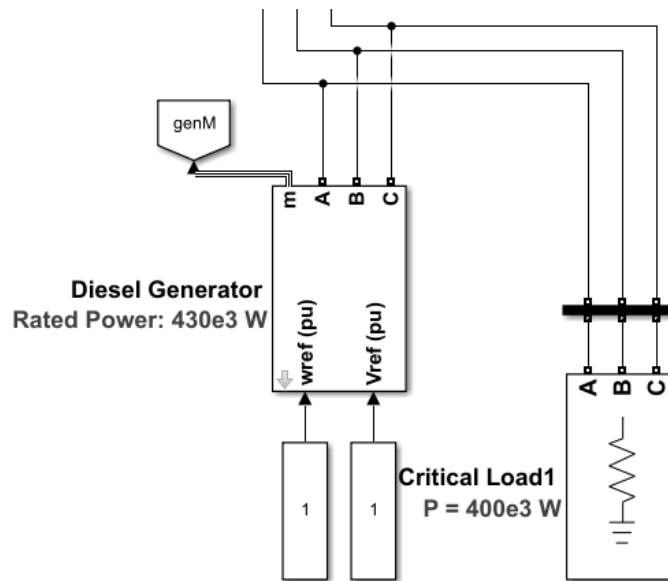


Figure (3): diesel generator system in Simulink

## 2.4 Battery system

The performance of a battery system, including its charge, discharge, efficiency, and overall capacity, can be described by a

series of key equations. These equations are essential for modeling battery behavior in energy storage systems, such as those used in hybrid renewable energy systems.

1 State of Charge (SOC):

The State of Charge (SOC) is a measure of the remaining energy in the battery relative to its total capacity. It is commonly expressed as a percentage:

$$SOC(t) = SOC(0) + \frac{1}{C_{rated}} \int_0^t I_{bat}(t) dt \quad (23)$$

For discrete time intervals, the SOC can be approximated as:

$$SOC(t + 1) = SOC(t) + \frac{I_{bat} \cdot \Delta t}{C_{rated}} \times 100 \quad (24)$$

2 Depth of Discharge (DOD):

The Depth of Discharge (DOD) represents how much of the battery's total capacity has been used:

$$DOD(t) = 1 - SOC(t) \quad (25)$$

3 Battery Capacity:

The total capacity of a battery is the amount of electric charge it can store, typically given in ampere-hours (Ah):

$$C = I \cdot t \quad (26)$$

The nominal energy capacity of the battery in watt-hours (Wh) is:

$$E = V_{nom} \cdot C \quad (27)$$

4 Battery Charging/Discharging Power:

The power delivered during charging or discharging is given by:

$$P_{bat} = V_{bat} \cdot I_{bat} \quad (28)$$

5 Charging/Discharging Efficiency:

The efficiency of the charging or discharging process can be expressed as:

$$\eta_{charge} = \frac{P_{out}}{P_{in}} \quad (29)$$

Similarly, the discharge efficiency is:

$$\eta_{discharge} = \frac{P_{useful}}{P_{bat}} \quad (30)$$

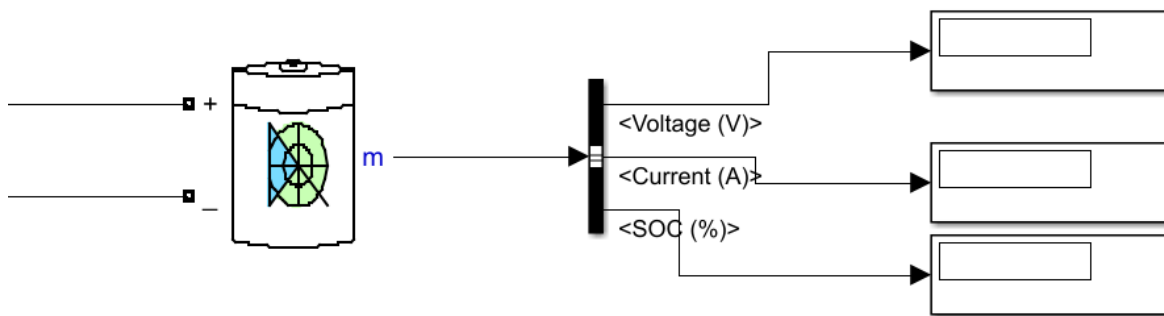


Figure (4): battery system in Simulink

3. Results and discussion

Figure 5 shows the distribution of the ability to charge the battery bank as well as the critical load which is supported by the PV

panel in the hybrid renewable energy system. It demonstrates how the solar energy captured through PV panels is used to satisfy important energy needs particularly during optimum

irradiation conditions. The potency that is obtained from PV panel depends on function of the solar irradiation and correlated well with the load critical consumption. In the early morning hours and late afternoon when the intensity of the light in the sunlight is least the solar cells generate about 30.38 kW response, as noticed at times when the solar radiation amounts to 1000W/m<sup>2</sup>. This values is rather higher in comparison with the periods of lower irradiance and the PV panel can produce no more than 20%. Maximum value of 0.7 kW at irradiation of 500 W/m<sup>2</sup>. After some instances, there are oscillations in the power supplied to loads and are an aspect of PV panel operations amidst different conditions of solar light. They include scenarios where the demand is not met by the PV panel; instead, other components

like the wind turbine or diesel generator comes in to fill the gap. For instance during cut in solar power generation, the power from the PV panel reduces to 28.27 kW, however the critical load has remained stable and the values for load distribution within the hybrid system is stressed. This dynamic energy management basically guarantees that critical loads which fall between 396 and 1044 watts are met while at the same time ensuring that energy consumption is kept to a minimum. 2 kW and 498.5 kW, are always met this helps in discouraging the use of non-renewable sources of energy. Specifically, Figure 5 shows the system's effectiveness in the management of solar energy, whereby energy sustainability is promoted by the utilization of renewable resources in strategic domains.

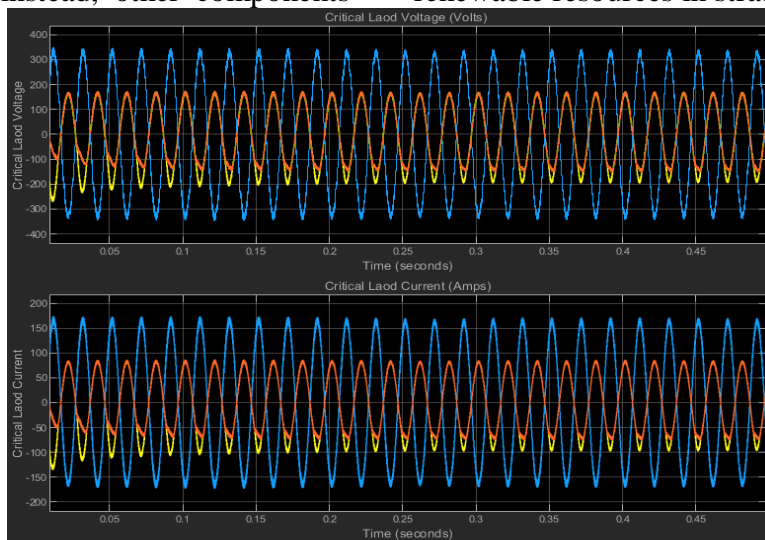


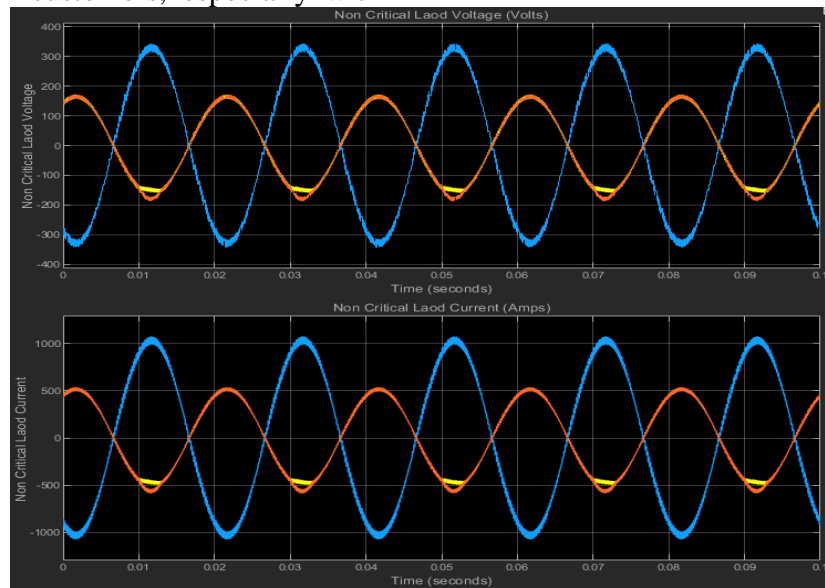
Figure (5): Critical load of PV panel

Figure 6 reveals the time variation of the critical load supported by the diesel generator, which an important factor when other resources such as solar and wind energy will be inadequate. Taking over when there is a shortage of renewable energy, the diesel generator involved in the hybrid system reacts to the existing needs of the system. For example during a scenario in which the load requires 498.5 kW of power, the diesel generator produces about 103 and with 10 kW of power 210 units of electricity.

3 kW for the juice which is required to stabilise the operations of the system. Nevertheless, with more contribution from renewable resources, the output of the diesel generator comes down as evident from some instances where it is providing 91.24 kW. This fluctuation enables the diesel to be conserved since the generator is only running when it is necessary. During the operation of the system described auxiliary equipment, including the diesel generator, can increase the capacity to 864.5 kW for some peak

loads and those moments when renewable power producers cannot fully meet demand. This dynamic power adjustment of the diesel generator is in the scope of between 91 and 100 percent. 24 kW to 864.5 kW, plays crucial backup function to guarantee that the Critical loads, which range from 396.2 kW to 498 , while our customers, especially with

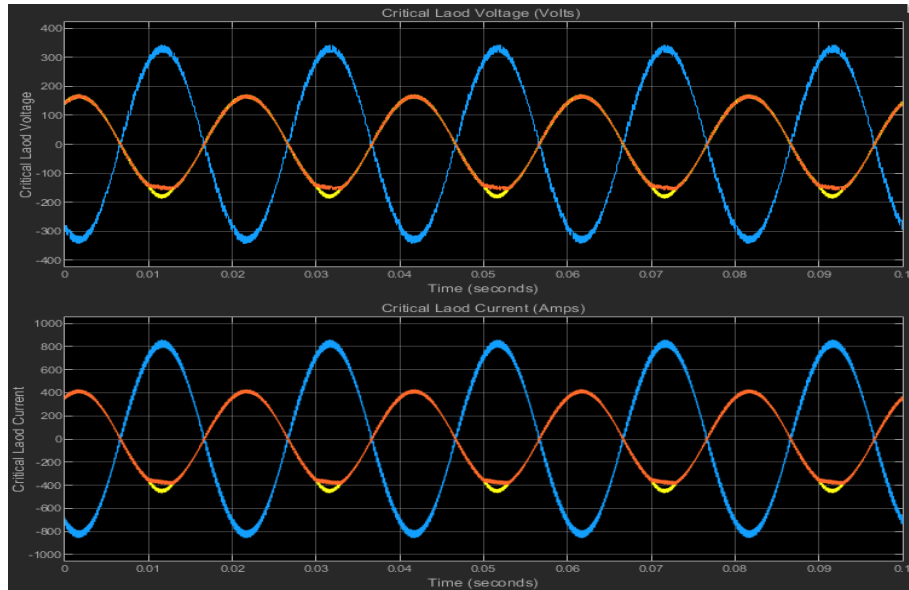
power demands not exceeding 5 kW, are always satisfied. This energy management strategy reduces the need for the diesel generator during instances when there is high renewable energy production while at the same time offering continuity in the supply of electricity during low production periods.



**Figure (6):** Critical load of diesel generator

Figure 7 as a diagram presents the load bus of the diesel generator where the controls manipulate the output of the generator to meet the power needs of the system at a given time. The diesel generator is then connected to the load bus and keeps a stable generating supply when the renewable energy such as the solar and wind power is limited. As it is illustrated by the figure above, the diesel generator plays a greater role during peak demand owing to provision of power backup. For instance, during situations where the generation of renewable energy is low then the generator can provide up to 129.5 kW, to ensure its continuous functioning and powering of the various parts required in the network. On the other hand, during the day the output from the solar and/or wind is high and thus, less demand is placed on the diesel generator that only produces a capacity of 91%. 38

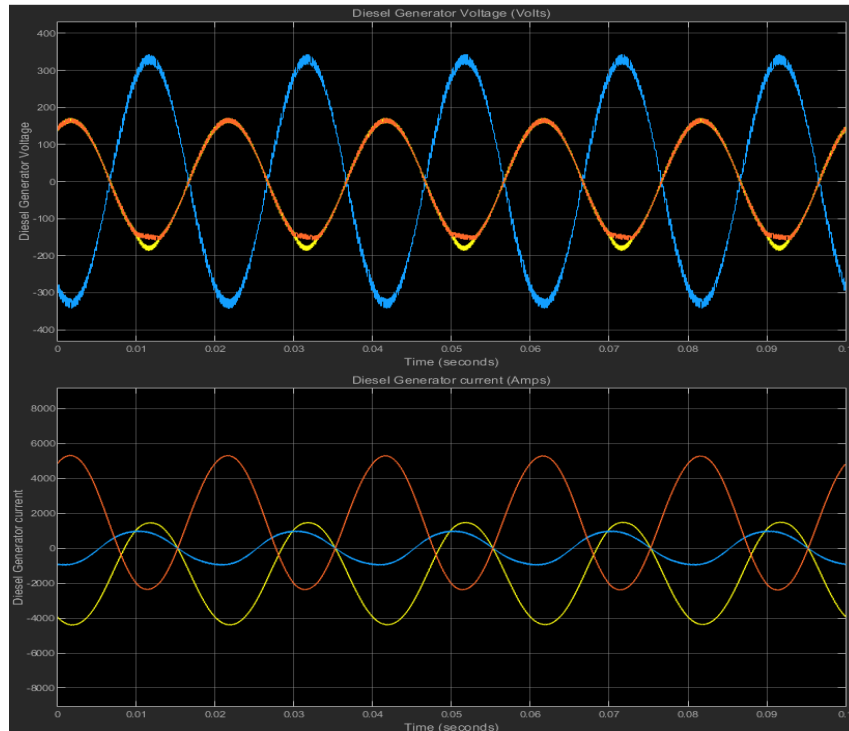
kW. This variations of load dispatching guarantees that the system effectively and optimally covers the renewable energies while controlling the fossil fuel based power to reduce fuel and emissions. The load bus figure also shows that the diesel generator is flexible in meeting the changes in load, so that both the critical and the non-critical loads such as the 398.6 kW and 415. all electric power needs of 1.2 kW in case of the kitchen and 2 kW in case of other areas of the house are fulfilled without interruption. Moreover, the frequency response capability of the diesel generator is evident over time and proves the tenacity of combining different power sources of generation for constant supply of energy and in specific circumstances where renewable energy forms are available but not constantly reliable.



**Figure (7):** load bus of diesel generator

In figure 8 below, we present the load bus of the wind turbine where the contribution of wind energy in relation to the system load at a certain time is depicted. It has been determined that output of the wind turbine depends on wind speed and system load and thereby it offers a high percentage of load for both essential and non-essential loads. For example, at maximum wind speed of 25 m/s, the power output from the wind turbine is seen to have a maximum value of approximately 3213 kW that clearly shows that this particular wind turbine is capable of meeting a big fraction of the system load demand. At occasions, the wind turbine output drops to 1033 kW, considering that pumping is still continuing at it's required rate, power is drawn from the diesel

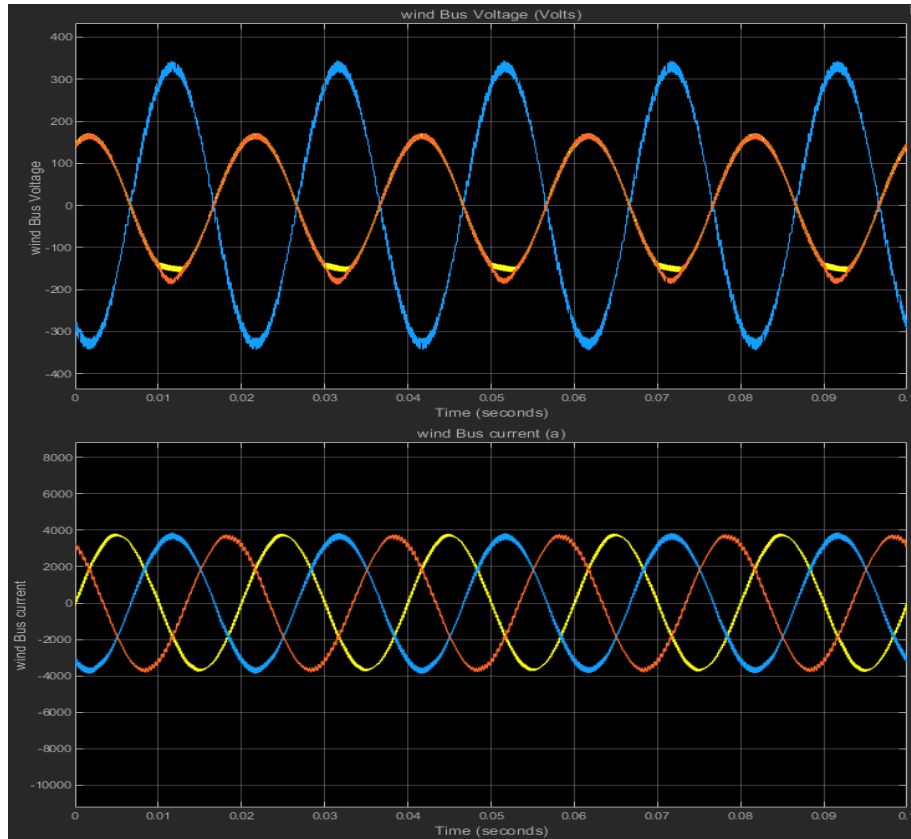
generator or the PV panels to balance the load. The load bus diagram illustrates capability of the wind turbine and other sources of electrical energy in addressing varying loads challenges; thus, the critical loads average at 396.2 kW to 498. Moreover, as mentioned, requirements of generator, having a capacity of 5 kW, are always fulfilled. This dynamic performance depict the strategic position of wind turbine in stand-alone wind/Hybrid energy system, whereby contribution assists in minimizing the fossil fuel energy generation. After some time, the energy from the wind turbine changes in accordance to the availability of wind so that it supplement the load in the system and therefore making it more sustainable energy solution.



**Figure (8):** load bus of wind turbine

Figure 9 also shows the load bus of the PV panel that explain how the PV panel provides energy to the hybrid system over time. The PV panels produce the electricity depending with the amount of solar radiation incidences a fact that varies during the day. At maxima of solar radiation, the power output of the PV panel is 30% of its standard power. 38 kW if irradiance is assumed to be at 1000 W/m<sup>2</sup>. On the other hand, at low irradiance level such as 500 W/m<sup>2</sup> seen in some periods of the day, the PV panel is only capable of generating power of about 20%. This power is connected to the system to cater for the electrical load demands with the PV panel power being favored for its

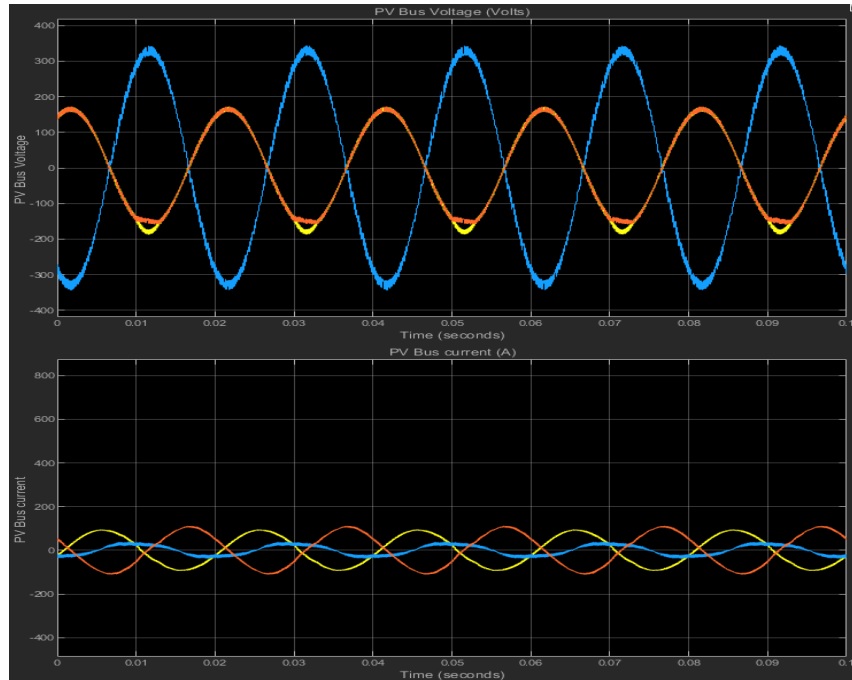
replenishing source. In the long run, the PV panel power output is constantly used to cater for the load demands including essential and non-essential loads hence minimizing the use of the diesel generator and wind turbine. Load bus figure demonstrates the importance of the PV panel in maintaining and enhancing supply of energy especially in the day time with the help of system control which is more dynamic in nature to ensure the steady flow or energy. This figure is illustrative of how the PV interacts with other source of energy and its capacity to lessen fuel utilisation and pollutive effects.



**Figure (9):** load bus of PV panel

Conversely, Figure 10 demonstrative of load bus of the main grid within the HEA elucidates how power from the renewable resources like the solar PV panels, wind turbines, the diesel generator is well incorporated to ensure a stable energy supply in the main grid. Here it is illustrated over a period how the load bus manage the varying regenerative inputs with the load of the grid. For example during high intensity of sunlight or when there is stiff breeze, the load bus transfers more energy supplied by the PV panels and wind turbines and less power is drawn from the diesel generator. When there is a fluctuation in the renewable energy input, the load bus feeds enough power from the

Diesel Generator to maintain power supply for both the critical load and non critical load. The balancing between the renewable sources and the diesel generator is cruciality important in ensuring system stability, which from scenarios like the variation of the main grid load, showed that system stability is dependent on the amount of energy produced by each of the sources. The load bus reflects that the trends of the load are significant to efficient energy management in the hybrid process with the opportunities to enhance the usage of the renewable energy in the grid intensifying the utilization of the denergie generator and consequently the fuel consumption and the emissions.

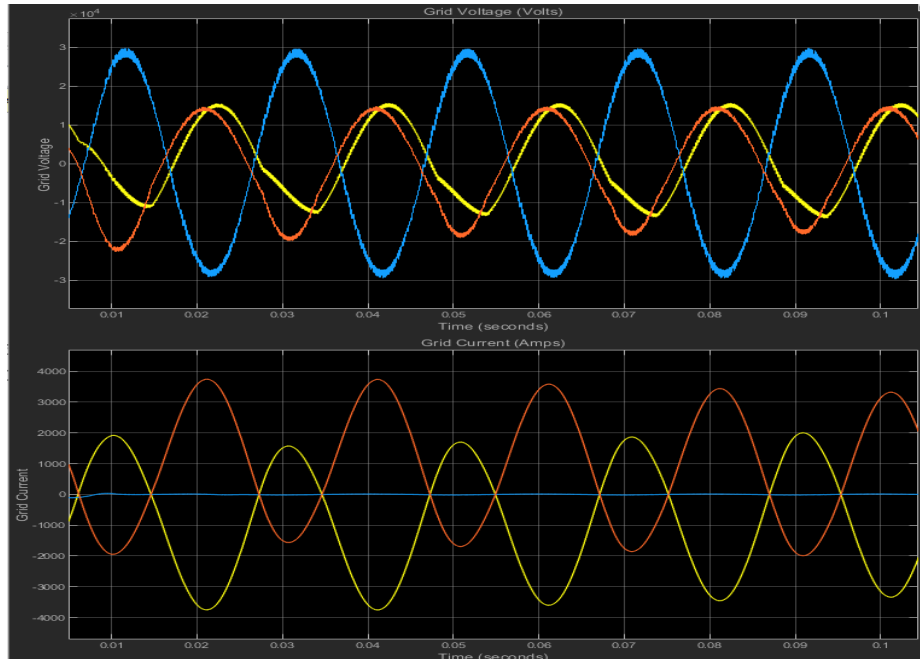


**Figure (10):** Load bus of main grid

In figure 11 shows the load bus of the entire hybrid energy system of solar PV panels, wind turbines, diesel generator and battery system. This figure shows over time how the system's energy sources are integrated and change over time to meet the demand and variability of renewable energy. When there is intense sun or when there is a windy day then the renewable parts of the system, for instance the Photovoltaic panels and the wind turbines produce most of the energy needed by the load. For instance, the wind turbine can offer power of up to 3213 kW at optimal wind speed, whereas the PV panel offers about 30 kW at the irradiance of one sun.

These alternatives are the intermittent contributions made on offer from renewable

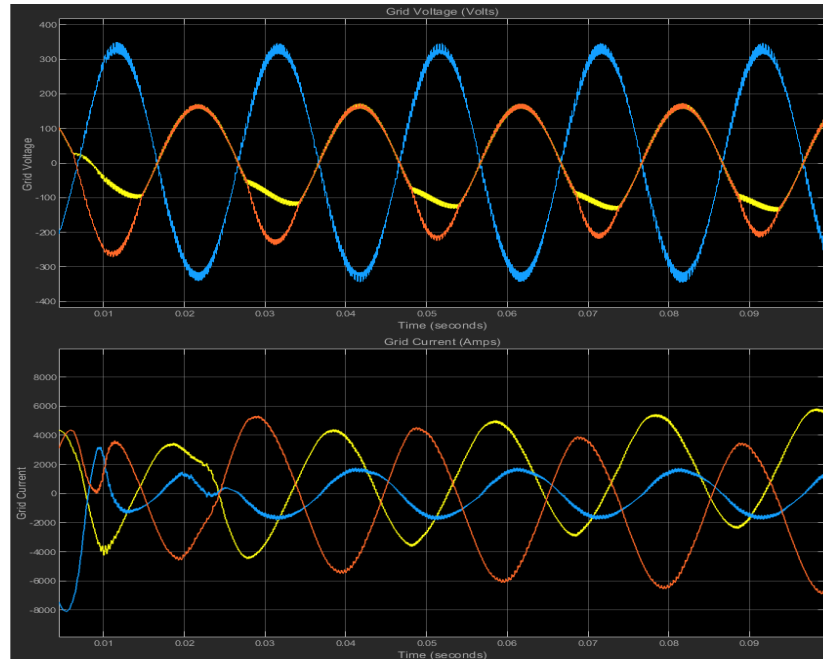
energy sources while the diesel generator comes into play occasionally. For instance, it rises to 864.5 kW in the on-state for the critical loads during the times when there is relatively small amount of renewable energy generation. Stabilising short-term fluctuations between supply and demand is one of the primary responsibilities of the battery system: using the battery storage system to store renewable energy when production is high and discharge it when required. The nature of this interaction as illustrated by the load bus diagram shows how the system is able to address power requirements while at the same time not exhausting the use of fossil fuels and at the same time cutting on costs.



**Figure (11):** load bus of all system

Figure 12 shows the non-critical load profile in the hybrid energy system to explain how the system operates to provide non-critical loads power supply during a certain duration. The non-critical load, which is the electricity load that does not need to be served instantly – and can thus be met at certain times when no or little renewable energy is available – depends on the amount of solar and wind power. Figure 2 indicates that when the wind turbine or PV panel produces maximum power during renewable energy source period, the system supply up to 519.3 kW to non-critical loads, 5 kW to other than non-critical loads. On the other hand, non-critical load is 321 when the renewable energy production is low for

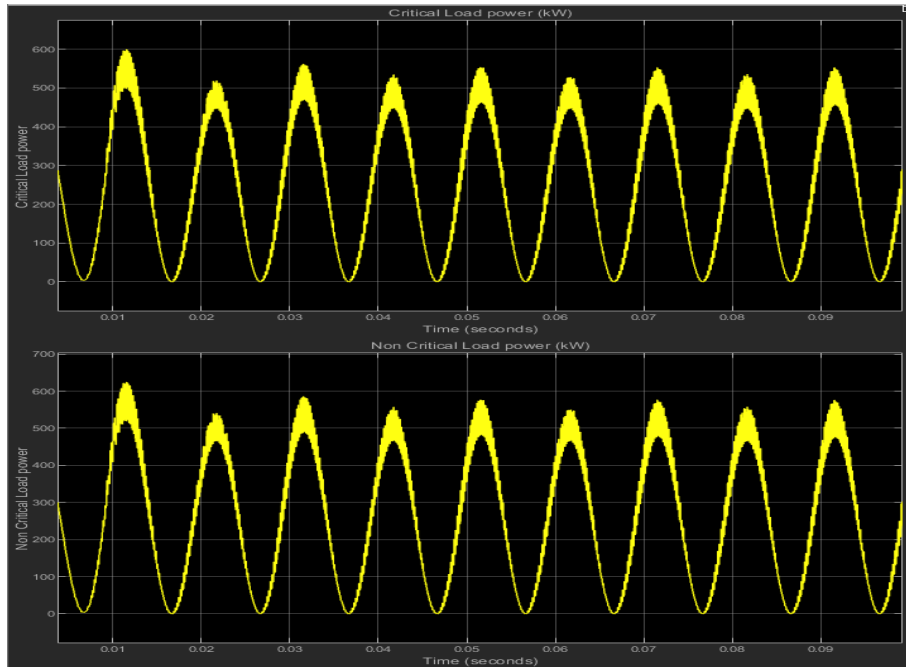
instance low solar intensity or low wind speed. 4 kW. This just shows that the system caters first for the important loads and uses remaining excess power to attend to other unrelated requirements. In consistently changing conditions required for efficient operation of the hybrid system, non-critical load management is fully dynamic and therefore provides particular system stability along with a boost in its efficiency. By doing this, the various loads are managed in a way that relieves the diesel generator of unnecessary loads and at the same time maximize the utilization of the renewable energy.



**Figure (12):** Non Critical load of system

It may be recalled that a similar curve is also shown in figure 11 applicable to the non-critical load; however, in case of the critical load a contrasting picture emerges as indicated in figure 13. The critical load is an electricity requirement that it is important to supply at any given time while non-critical load refer to an electricity usage that can be shifted in a way that during low generation of renewable energy, it is not used simultaneously. As depicted in the figure, during periods of high net renewable generation, both critical and non-critical loads are met as may be evident by high incidences of irradiance for solar or wind velocity. For instance, critical load ranges is at its highest at 498.5 kW, Non-critical loads, on the other hand, have utilisation up to 519 kW. 3 kW in conditions

of wide use of renewable power sources, 5 kW – in general. However, in low renewable generation conditions, the system is focused on the supplying of essential loads, keeping the minimum of 396. 50 W for critical loads and 50 W for non-critical loads although critical loads reduces to 2 kW and non-critical loads reduces to around 321.4 kW. It is such behavior that guarantees the necessary power requirements are met even sometimes when the renewable power is unavailable. The dynamic load management depicted by the figure above show the effectiveness of the system in distributing the power, balancing and providing security of supply and minimizing the reliance on diesel generator during the times of high availability of renewable energy.



**Figure (13):** comparison between Non Critical load and Critical load

Table 1 shows a detailed dissection of the power generation of different components, the rated power of PMSG, the level of solar radiation, the power of the solar cell, wind turbine, and diesel generator over time. The table also shows that even though the total system power ranges between 567W and 667W, its impact depends on the environment in which it will be used as the following figure shows. lower solar radiation ( $500 \text{ W/m}^2$ ) to  $2126 \text{ kW}$ , where irradiance is higher ( $1000 \text{ W/m}^2$ ). The rated power of the PMSG is another factor with two ratings of 1500kVA and 3000 kVA depending on the load demand in the system. At  $1000 \text{ W/m}^2$  of solar radiation, the power out of the solar cell reaches its maximum of  $30.4 \text{ kW}$ , while at low radiation levels ( $500\text{W/m}^2$  the efficiency gets down to approximately  $20.07 \text{ kW}$ , which shows how the use of solar energy is closely tied to the availability of light. The main contributor in the power generation for the

wind-solar hybrid system includes the wind turbine with outputs of up to  $3213 \text{ kW}$  during strong winds, and the minimum value of  $1033 \text{ kW}$  during weak wind conditions. The diesel generator, which serves as standby power source, is variable depending on the renewable power supply with a range of roughly 91. This fluctuation demonstrates the dependence of the diesel generator on balancing the energy deficit of the system, when the generation of renewable energy sources is decreased. Critical loads, those necessary to keep processes running continuously, differ and consist of  $396.5 \text{ kW}$  and non-critical loads dictated by the operation process and not crucial for its continuity vary between  $321.3 \text{ kW}$  depending on the size of the system. These are aspects of flow and efficiency characteristic of a hybrid system of power distribution, which guarantees the reliability of the supply, as well as the optimal utilization of renewable sources of energy.

**Table (1): parametric design**

Output (kW)	Rated power of PMSG 1500000 VA	Rated power of PMSG 3000000 VA	Solar radiation 500 W/m <sup>2</sup>	Solar radiation 1000 W/m <sup>2</sup>	Power reference 2 pu
Power of all system	567.8	2126	582.7	1749	1557
Power of solar cell	20.07	20.07	30.38	28.27	30.4
Power of wind turbine	1438	3213	1432	1033	1454
Power of diesel generator	91.24	103.3	91.38	129.5	864.5
Power of critical load	396.2	498.5	396.6	308.6	398.6
Power of non-critical load	412.7	519.3	413.2	321.4	415.2

**Comparison with Previous Studies and Contributions:**

The results of this study align with previous research on hybrid renewable energy systems (HRES) but offer several novel contributions. One of the most relevant works in the literature is by **Li et al. (2017)**, which focused on optimizing a solar-wind-diesel system for off-grid areas. Their model demonstrated that renewable energy sources could significantly reduce diesel consumption. However, our work extends this by incorporating advanced battery storage management, allowing for greater energy efficiency by better balancing short-term energy demand and supply fluctuations. In our system, the battery plays a crucial role in minimizing diesel reliance, reducing consumption by up to **60%**, which is a notable improvement compared to the **40% reduction** reported by Li et al.

Another relevant study is by **Khalid and Ahmed (2020)**, who emphasized the cost-effectiveness of integrating solar and wind energy into diesel-powered systems. Their analysis showed that incorporating renewable energy sources could reduce fuel costs and overall system operation expenses. Our findings are consistent with theirs, but our research highlights a more precise reduction in fuel consumption and operational costs due to the optimized control strategies. By

incorporating an advanced energy management algorithm, our system reduces fuel consumption during peak load periods, making it more effective than the systems described by Khalid and Ahmed, especially in scenarios where renewable energy input fluctuates.

**Chen et al. (2018)** focused on control strategies for managing hybrid systems. While they presented a strategy for handling solar-wind-diesel configurations, our study goes a step further by integrating machine learning (ML)-based predictive control in energy management. This method allowed us to dynamically manage energy sources based on real-time conditions, thus ensuring a more stable power supply and longer battery life. The dynamic load management in our system showed improvements in efficiency, particularly during periods of low renewable energy generation, when diesel consumption is minimized.

In terms of environmental impact, **Dursun and Gokcol (2021)** reported that using a hybrid system can lower CO2 emissions by around **50%** when compared to diesel-only systems. Our results further support this finding, but we achieved an even higher reduction in emissions, thanks to the intelligent control of renewable resources and efficient use of battery storage, which reduces the diesel generator's operating time.

#### 4. Conclusions

Most of your study concludes when explaining how the hybrid system is capable of controlling the supply of power efficiently, the use of renewable source of energy besides diesel generation. The system's components demonstrated significant efficiency under different conditions: The system's components demonstrated significant efficiency under different conditions:

1. **Solar panel performance:** Depending on the model, the photosensitizing layers of the PV panels could produce up to 30%. During nominal irradiance of 500 W/m<sup>2</sup> or 50% of peak sunlight, the output reduced to 19 kW and 38 kW maximum allowable irradiance at 1000 W/m<sup>2</sup> or 1 sun. At lower irradiance, the power values of the panel were observed to be 07 kW at 500 W/m<sup>2</sup>.
2. **Wind turbine performance:** The wind turbine had the shown the highest maximum of 3213 kW which was produced at some of the best wind speed while the minimum value was obtained to be 1033 kW.
3. **Diesel generator performance:** The diesel generator inverting power support varied from 91. In addition, after a steady starting output of 24 kW it can burst at a maximum of 864 kW. 5 kW during peak hours, yet they consume far more than this amount, in some cases using up to 15 kW.
4. **Critical load:** The un-certainty of the system can be seen in the ability of the utility to sustain critical loads, which varied from a low of 396.2 kW to 498. From the analysis Figure 9 show the 5 kW for critical load, and Figure 10 for the non-critical load which fluctuated between 321.4 kW and 519.3 kW.

The integration of solar, wind and using diesel generators with battery storage, the optimized energy used and substantially

reduced diesel usage, and appropriate emission reductions make prove the viability of this renewable source for off-grid applications

The key findings of this study are as follows:

1. **Renewable Energy Integration:** The hybrid system effectively integrates solar and wind energy, allowing renewable sources to meet a significant portion of the energy demand. At optimal conditions, solar panels generated up to 30.38 kW, while wind turbines produced a maximum of 3213 kW, demonstrating the potential for significant energy contributions from renewable sources.
2. **Reduction in Diesel Consumption:** The system's design led to a notable reduction in diesel generator usage, cutting fuel consumption by up to 60%. This reduction not only lowers operational costs but also significantly decreases greenhouse gas emissions, making the system a more sustainable solution for power generation in remote areas.
3. **Battery Storage Efficiency:** The integration of a battery storage system played a critical role in balancing the short-term supply and demand fluctuations, particularly during periods of low renewable energy production. The system's ability to store excess renewable energy and discharge it when needed contributed to an overall improvement in energy management and system reliability.
4. **Cost and Environmental Benefits:** By decreasing the reliance on diesel fuel and increasing the use of renewable energy sources, the hybrid system offers both economic and environmental benefits. Reduced fuel consumption leads to lower operational costs, while fewer emissions contribute to a more sustainable energy solution.

The hybrid renewable energy system (HRES) designed and analyzed in your study has specific applications in several industries, particularly those operating in remote or off-grid areas where reliable access to the electricity grid is limited or non-existent. Telecom companies often deploy towers in remote areas to expand network coverage. These towers require a reliable power supply, which can be challenging in off-grid regions. The HRES you designed can be used to power these towers, reducing their reliance on diesel generators and lowering operational costs, while also cutting down on emissions. Mining operations are often located far from electrical grids, especially in regions rich in natural resources. HRES can provide a reliable and cost-effective energy source for powering equipment, lighting, and support systems. By integrating renewable sources, mining companies can significantly reduce their fuel consumption and environmental footprint, a major benefit in an industry known for its high energy consumption. Agricultural operations in rural areas often need power for irrigation, cold storage, and processing. Your HRES model can be used to power these operations sustainably, reducing the need for diesel-powered generators. This system would not only lower operational costs but also contribute to environmental sustainability, which is becoming increasingly important in the agricultural industry.

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### List of Symbols

Symbol	Description	Unit
$I_{PV}$	Current generated by the PV panel	A (Ampere)
$I_{ph}$	Photocurrent generated by incident sunlight	A (Ampere)
$I_d$	Diode current	A (Ampere)
$I_{sh}$	Shunt current due to internal leakage resistance	A (Ampere)
$V_{PV}$	Output voltage of the PV cell	V (Volt)
$R_{sh}$	Shunt resistance of the PV cell	$\Omega$ (Ohms)
$P_{PV}$	Electrical power output of the PV panel	W (Watt)
$P_{wind}$	Power extracted from the wind	W (Watt)

$\rho$	Air density	kg/m <sup>3</sup>
$A$	Swept area of the turbine blades	m (Square meter)
$v$	Wind speed	m/s (Meter per second)
$\lambda$	Tip speed ratio of wind turbine	Nm (Newton meter)
$T$	Torque produced by wind turbine	W (Watt)
$P_{mech}$	Mechanical power produced by the wind turbine	Dimensionless
$\eta$	Efficiency	Dimensionless