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Research article

Improved utilization of hybrid energy for low-income houses based on energy consumption pattern

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Abstract: The adoption of solar photovoltaic and small wind turbine hybrid energy systems in residential applications has picked up promising development around the globe. However, the uncertainty of renewable energy generation associated with the reliance on climate conditions is one of the factors which affect the reliability of the system. Therefore, there is a need to develop an energy management scheme for improving the reliability of the system. One of the drawbacks of hybrid renewable energy systems is the high investment cost, particularly looking at low-income family units. This present paper, an extension of the preceding work, focused on the development of an energy utilization scheme of a hybrid energy system particularly for low-income houses based on energy consumption patterns. The utilization scheme is developed using computational methods in a MATLAB environment. Energy storage systems considered in this work are electrochemical batteries and small-scale flywheel energy storage (kinetic energy storage). Utilizing hybrid energy based on consumption patterns has lowered the capacity of the system's components, resulting in a $900.00 investment cost. The flywheel energy storage is prioritized to supply high-wattage loads while the battery is prioritized to supply average loads, resulting in a 33.9% improvement in battery health. This hybrid system contains a high proportion of renewable energy and reduces annual electricity costs by 96.7%. The simulated results on MATLAB software showed an improvement in terms of energy utilization of a hybrid power system. The cost of utilizing energy is reduced by effectively utilizing more renewable energy sources, with a resultant reduction in electricity bills.

Keywords: solar photovoltaic; small wind turbine; hybrid systems; renewable energy; consumption pattern; energy storage; low-income

Nomenclature: PV: Photovoltaic; WT: Wind turbine; P_{PV}: Output power produced by the photovoltaic solar module; P_{Nom}: PV power at the nominal conditions; G: Incident irradiance in W/m^2; NOCT: Nominal operating temperature of the cell; G_{STC}: Irradiance at standard test condition; T: Ambient temperature; α: Coefficient of maximum power in %/°C; P_m: Mechanical output power; P_a: Air power; C_p: Power coefficient; ρ_a: Density of air; A_{tb}: Area swept; V_a: Velocity of air; P_{WT}: Output power produced by the wind turbine; P_x: Essential loads; P_y: Standard loads; P_z: High loads; SOC: State of charge; SOC_B: Battery state of charge; SOC_F: Flywheel state of charge; C_{bat}: Capacity of the battery storage; E_D: Daily energy demand; DOD: Depth of discharge; E_k: Kinetic energy of a rotating mass; ToU: Time of use; LCOE: Levelized cost of energy

1. Introduction

Studies on the application and utilization of hybrid energy systems in residential households are receiving considerable attention [1]. The high cost of producing electric power from conventional sources and other challenges associated with environmental impacts has resulted in high penetration of renewable energy sources as the alternative means of generating electric power at a low cost. Despite the high cost of energy, one of the studies reviled that 55% of Sub-Saharan Africa still lives with no access to electricity [2,3]. About 85% of the generated electricity in South Africa is coming from coal-powered stations, and as a result of burning huge amounts of coal, coal-powered generating plants are the major contributors to the issues concerning contamination of the environment [4]. Access to electricity and imbalances regarding the standard of living is profound in South Africa. Outcomes reveal that energy poverty is a major challenge in South Africa. One of the measurements of energy poverty is affordability and thus remains an issue for most South African families [5]. Investigation reveals that the amount of money spent on monthly electricity bills in South African households has surpassed the energy poverty threshold set by the department of energy [6]. Renewable energy systems are mostly preferred as the source of electric power for mitigating the challenges associated with conventional sources. However, the high investment cost to implement such systems is a major drawback, particularly for family units. In any case, the issues of framework affordability and levelized cost of energy (LCOE) ought to be attended to as they pose major challenges to low-income houses. Most of the studies are usually centered on load management which includes planning of tasks in accordance with price scheme [7].

Energy consumption pattern varies from house to house, this could be influenced by the classification of settlement (rural or urban), salary earning, age, work status, number of inhabitants, etc. There is no device that can precisely depict human behavior in terms of power utilization. However, there are a number of devices mindful of coordinating users' energy utilization patterns. Day to day schedules of energy users is significantly affected by social, natural, and financial variables. The load profile is greatly shaped by the financial income of the household [8]. In most cases, low-income houses in rural settlements, utilize electric power for refrigeration, lighting, television, dish satellite, radio, kettle, ironing, cell phone charging, and other small applications. Investigative studies reveal that a high percentage of low-income groups in rural settlements use firewood for cooking [9]. There is a need to utilize hybrid energy based on energy consumption patterns and load demand inside a household. Most hybrid power systems are sized based on the total demand within the household. However, it is not common for users to utilize all their appliances at once, and in addition to this, a few of the high power rating appliances such as kettle (for boiling water), and iron are utilized for a short period and not frequently.

This work focuses on developing an energy utilization scheme of a hybrid power system for low-income houses. The utilization scheme is based on the energy consumption pattern of an individual household. The hybrid system in this study consists of PV solar, small wind energy, battery storage, and small mechanical flywheel energy storage. Electrical loads (in-house appliances) are categorized in terms of their priorities and amperage. The utilization scheme detects the time of use period, the type of load connected, and the status of available sources at the time of energy demand then take a decision on which source/mixed sources to utilize. As the study seemly concentrates on low-income houses, one of the major drawbacks of replacing or integrating the grid with renewable energy sources is the high investment cost.

2. Related works

Despite the high penetration of renewable energy systems in various sectors, hesitations in implementing renewable energy systems due to their operation instability associated with the dependency on climate conditions and high capital costs exist or emerge [10,11]. Numerous research demonstrated the integration of diverse renewable resources with various energy storages [12–18]. These studies employ various energy management techniques, strategies, and approaches. Improved technologies in energy management include but not limited to shifting of loads, controllable loads, improved storage devices, and distributed energy generation [19]. Energy management approaches of off-grid hybrid systems consisting of PV solar and energy storage have been presented. The presented approach concentrated on managing the stored energy on the storage devices and protecting the energy-storing devices from overcharging/discharging. The results showed good improvement in reducing the loss of power supply probability (LPSP) [20,21]. However, the presented works make use of one renewable energy source which is only effective during sun hours and this reduces the reliability of the system even though the storage system is available. An approach of load scheduling on a grid-connected hybrid system consisting of PV solar and battery storage is presented, this approach shifts some of the loads to be used when the tariff is low therefore this approach results in energy savings [22]. However, customers' flexibility in utilizing an appliance at any period is reduced. Various studies have implemented advanced load monitoring techniques and applied them in different renewable energy technologies which include load shifting. However, load behavioral pattern has not been used to help in effectively utilizing hybrid renewable energy in residential applications.

A hybrid PV/wind system is proposed to reduce electricity costs at a Lafarge cement plant. Using Lithium-Ion battery banks to store extra energy led to a significant decrease in annual electricity costs [23]. The proposed approach appears economically viable for business and industry. However, the incorporation of lithium-Ion batteries into residential applications could incur substantial initial investment and replacement costs throughout the product's lifetime. Using the proposed methodology and the HOMER software, a hybrid PV-Wind system is optimized. The proposed technique determines the placement of hybrid components to ensure the lowest net present cost and the highest level of dependability [24]. The results of the study indicate that the installation of the system can result in decreased system expenses and increased system reliability. Moreover, the proposed solution reduces the size of the battery bank. The objective of the optimization technique developed by [25] was to minimize net current costs and carbon dioxide emissions. This method determines the energy flow from each component of the hybrid system and tests the energy balance between several scenarios in which solar radiation and wind speed variations are taken into account. The results demonstrate a size reduction in the hybrid system. Furthermore, the results demonstrated that the addition of battery storage raises the cost of energy in every scenario studied. A study investigated the power management of a hybrid energy system consisting of photovoltaic solar and wind turbine as major sources and a flywheel storage device [26]. The management technique relies on peak restriction and load shedding, and the findings indicate a decrease in grid energy use. The complementing effect of hybridizing the battery and flywheel on battery aging for a PV-powered application was investigated in [27]. In a PV-powered application, the hybrid of a battery and flywheel had a lower capital cost and life cycle cost than the battery alone, according to the findings. Moreover, a sensitivity study found that a larger discharging current could significantly impact the battery's aging, although variations in corrosion and degradation limits have a negligible impact on the battery's aging. Another study conducted the overview of the various applications of flywheel energy storage [28]. The advantages of flywheel storage were highlighted, including its high power and energy densities, high efficiency, good dependability, long lifespan, and low maintenance requirements. The study indicated that flywheel energy storage is suited for applications requiring short-term, high-power bursts.

Despite significant advancements in renewable energy technologies, no established research analyses the activities conducted in a home and employs renewable energy based on behavioral pattern usage. In addition, most of the offered work does not focus on low-income residential communities. There is a need to utilize energy based on how customers utilize their loads, therefore this strategy is predicted to reduce the size of PV-Wind systems after careful examination of the literature. This work focuses on an energy utilization approach which is based on user load behavioral patterns. Hybrid energy sources are utilized based on the consumption pattern at different operating times. Hybridized energy storage which is the combination of battery and flywheel energy storage is included and these storage(s) are utilized effectively for their operational features. A flywheel energy storage is prioritized for supplying high-wattage loads that are frequently connected for short durations, such as a kettle, iron, or microwave. The battery storage is intended to supply average loads when demand exceeds the combined PV solar and wind system generation. A grid serves as the primary backup supply, meeting demand only when there is insufficient generation from renewable sources and when the amount of stored energy is low.

3. Contribution of the study

This study develops a small-scale, grid-integrated hybrid power system comprised of photovoltaic solar panels, a small wind turbine, batteries, and flywheels for energy storage. The utilization of energy derived from renewable sources is reliant on how household appliances are utilized. The size of the solar panels and wind system does not account for the peak demand caused by high wattage appliances that are planned to be connected for a short period of time. To supply such high wattage loads, however, flywheel energy storage is incorporated and prioritized. Using a small-scale hybrid system with an expected low investment cost, the applied energy utilization technique is expected to demonstrate a substantial improvement in terms of fully satisfying demand. The flywheel storage prevents the battery from supplying wattage loads, thereby restricting the battery's deep discharge cycles.

4. Renewable energy resources and system sizing

4.1. Solar photovoltaic and location resources

A solar photovoltaic system converts sunlight energy into electricity (voltage). The power provided by the sunlight is called irradiance (measured in watts per square meter). Solar radiation arrives on the earth’s surface at an approximate power density of 1000 W/m^2. Numerous variables account for sun-oriented energy that is received by a given site, such as location, time of the day, and climate conditions. The PV solar produces the maximum power, and the corresponding voltage and current when the standard test conditions are met, otherwise the characteristics of the PV module need to be rectified. The corrections on the produced power and the corresponding current and voltage with the change in irradiance (G) are as follows:

$$P_{(t)} = P_{STC} \times \frac{G_{(t)}}{G_{STC}} \tag{1}$$

$$V = V_{STC} \tag{2}$$

$$I_{(t)} = I_{STC} \times \frac{G_{(t)}}{G_{STC}} \tag{3}$$

The STC subscript indicates each value at the standard test condition. Equation 4 [29], which represents the output power of the PV module and fed into the inverter is given as follows:

$$P_{PV(t)} = P_{nom} \times \frac{G_{(t)}}{G_{STC}} \left[1 - \alpha \left(T_{(t)} + \frac{G_{(t)}}{800} [NOCT - 20] - 25 \right) \right] \tag{4}$$

T is the ambient temperature, P_{nom} is the PV power at the nominal conditions or at STC, G is the incident irradiance in W/m^2, α is the coefficient of maximum power in %/℃ and NOCT is the nominal operating temperature of the cell. Figure 1 shows the average monthly solar radiation for Madimbo village in the Northern part of Limpopo province. These meteorological data are obtained through the NASA data access viewer [30].

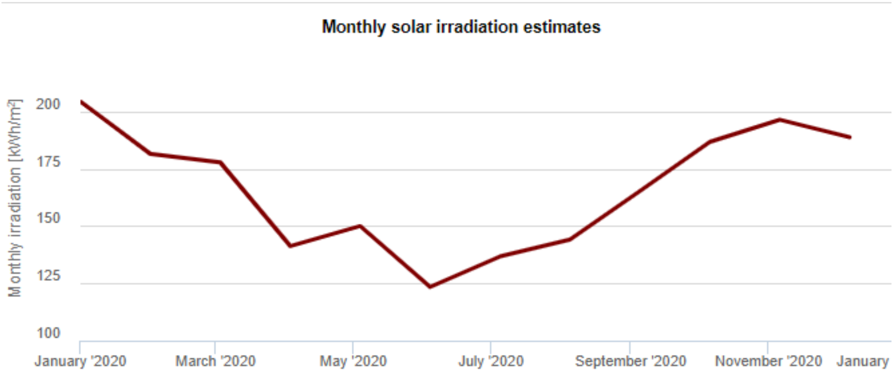


Figure 1. Monthly solar irradiation of madimbo village [30].

4.2. *Wind energy and location resources*

Wind energy is a form of kinetic energy arising as a result of a heat gradient impact on the surface of the earth, forming moving air. Wind energy systems are commonly used in the application of electricity generation. A wind turbine is used as a prime mover to convert the kinetic energy in the moving air into rotational energy (mechanical energy), the produced rotational energy is used to turn the shaft of the generator to produce electricity. The produced power from wind energy is unsteady due to variations in wind speed, the direction of the wind, structural insecurity due to overwhelming guts, and cyclonic storms. The relationship between air power and turbine mechanical power is demonstrated by the following Eqs (5 to 7) [31]:

$$P_m = C_p P_a \tag{5}$$

where P_m is the mechanical power, C_p is the power coefficient (which typically varies from 0.2 to 0.4 in a practical situation), and P_a is the air power. Air power is calculated using the following equation:

$$P_a = \frac{1}{2}\rho_a A_{tb} V_a^3 \tag{6}$$

where ρ_a is the density of air, A_{tb} is the area swept, and V_a is the velocity of air. Equation 6 can be substituted into Eq 5 to yield the mechanical power of the wind turbine.

$$P_m = \frac{1}{2} C_p \rho_a A_{tb} V_a^3 \tag{7}$$

The produced mechanical power can be increased by increasing the swept area of the blades, or by increasing the speed of air. In this study, the length of the blades will be fixed resulting in a fixed swept area, hence the variation of produced power will depend on the speed of air. The average wind turbine power can be calculated using the below equation [24]:

$$P_{WT(t)} = \begin{cases} 0, & v_{(t)} < v_{in} \\ P_{rated}\left(\dfrac{v_{(t)}^2 - v_{in}^2}{v_{rated}^2 - v_{in}^2}\right), & v_{in} < v_{(t)} > v_{rated} \\ P_{rated}, & v_{rated} < v_{(t)} > v_{out} \end{cases} \tag{8}$$

P_{WT} is the wind turbine power, P_{rated} is the nominal power rating of the wind turbine, v is the speed of wind, v_{in} is the cut-in speed of wind, v_{out} is the cut-out speed of the wind. The average monthly wind speed for Madimbo village is obtained through NASA data access viewer [30] and shown below in Figure 2.

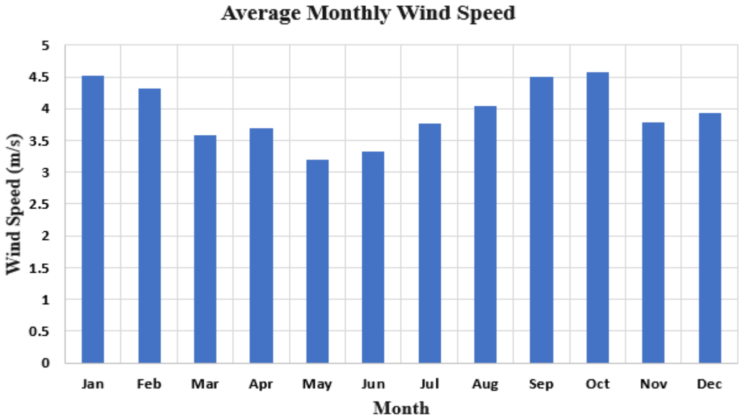


Figure 2. Average monthly wind speed of Madimbo Village [30].

4.3. *Load profile analysis and system sizing*

In this study, the load profile is assumed to be taken for social housing of low-income earners. This social housing consists of 4 rooms, and dwellers utilize electric energy for switching on certain appliances such as lights, kettle, microwave, iron, television, DSTV decoder, radio, fridge, and other small loads such as phone chargers. The occupant of this typical household uses firewood for cooking and uses an electric kettle to boil water in the morning when preparing to go to work, the occupants are also assumed to use iron later in the evening after work. A small microwave is used to warm food for about 10 minutes throughout the day. The 24-hour load demand for a typical household is assumed based on the appliances which are utilized taking into consideration the availability of the occupants throughout the weekday. Energy consumption of this selected low-income household does not vary by a huge margin during weekdays and weekends, this is influenced by the activities which are performed within the household where electricity is mainly used for lighting, while the variation in load pattern might be caused by the application of small loads such as TV, Radio, Cell phone charger, etc. The daily energy consumption and peak load demands are 3.16 kWh and 1.85 kW respectively. Distinctive load monitoring approaches are undertaken to point out the loads being served at the time of operation. This study will consider the application of a load monitoring approach hence domestic appliances are classified into three distinct groups (P_x, P_y, and P_z) with respect to their power rating (the product of ampere and voltage) and prioritization. Essential loads are denoted as P_x and these loads are given first priority in terms of energy utilization, they should be supplied at all times when their needs arise.

Standard loads (P_y) are classified as the type of loads that are given less priority, these loads can be ignored during low energy density. However, energy users can decide to move standard loads to essential load sockets driven by relays if they need to connect them irrespective of cost-saving method. This is done to increase users' flexibility and not to reduce their energy use comfort. High power rating loads are also given first priority though they are categorized by their high wattage ratings, these loads are denoted as P_z. Table 1 shows the classified domestic appliances, looking at the typical household of low-income earners from rural settlements. The daily load demand of a typical low-income household is illustrated in Figure 3.

Table 1. Low-Income household appliances.

P_x (Essential loads)	P_y (Standard loads)	P_z (High loads)
Fridge	Television	Electric kettle
Inside lights	Satellite dish	Microwave
Outside lights	Radio	Iron
	Phone chargers	
	Others	

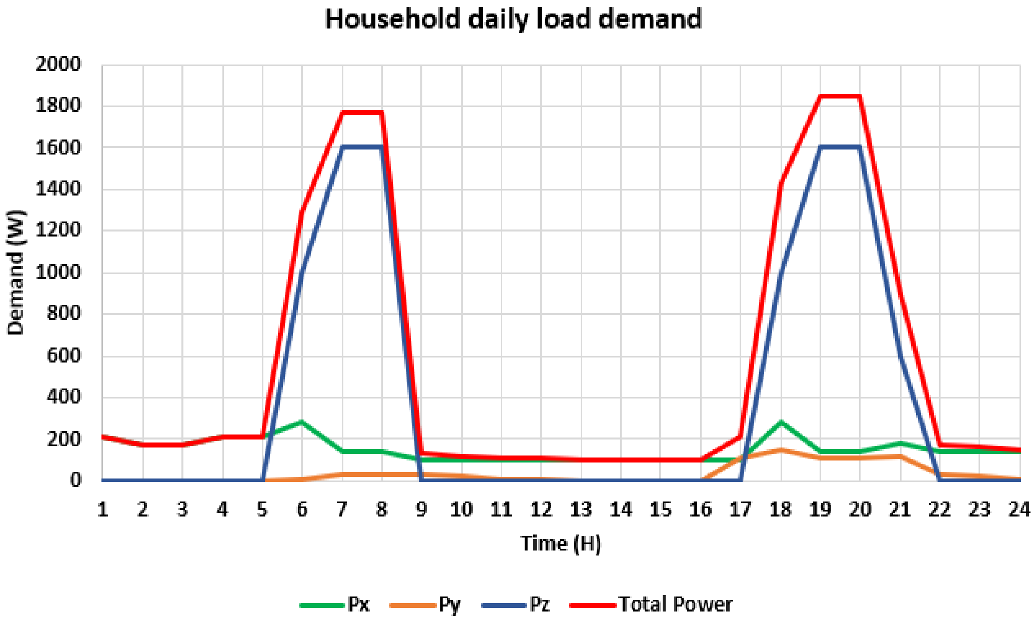


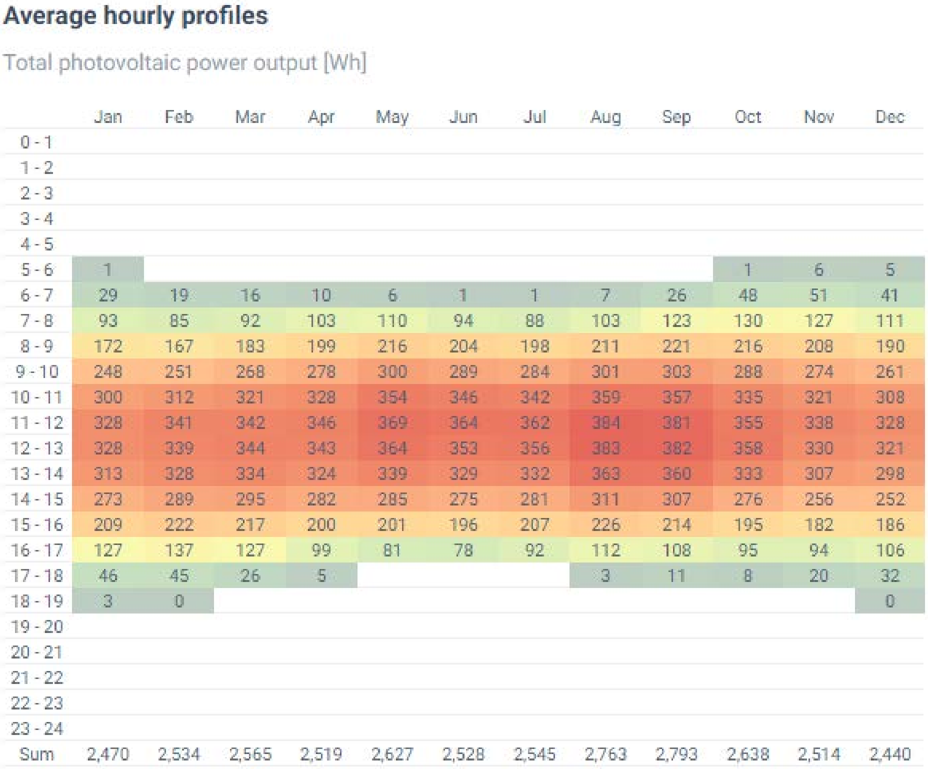
Figure 3. Daily load demand of low-income household.

4.4. PV solar system sizing

The sizing of a PV solar system is determined based on the behavior of load demand during sun hours at the selected location (typically from 08h00 to 16h00). This solar system sizing method does not consider all the loads within the household, high wattage appliances highlighted in Table 1are not included when sizing the solar system. However, the sizing method considers fully satisfying the storage devices during the generation of solar output. The stored energy is then utilized later to meet high wattage appliances, the first priority is given to the flywheel storage followed by the battery storage. The demand of a selected household varies from 1770 W at 08h00 to 100 W at 16h00. With the exclusion of high wattage appliances, the demand varies from 170 W to 100 W at the same respective time range (08h00 to 16h00). A selected location (Madimbo) which is found in the northern part of Limpopo province in South Africa has a daily sun peak hour of 5.69, this meteorological data is obtained from the Global Solar Atlas website. Considering a single source as a PV solar system with an energy demand of 3.16 kWh and 5.69 daily peak sun hours, Eq 9 is applied to calculate the actual size of the PV Array.

$$\text{PV Array}\left(kW\right) = \frac{\mathit{Daily}\ \text{Energy Demand}\left(kWh\right)}{\text{Peak Sun Hours} \times \text{Solar Efficiency}} \tag{9}$$

The size of the PV array is calculated as 0.74 kW (740 W) with a solar panel efficiency of 75%. This PV array size is when only one source is applied but this work concentrates on the hybrid system which consists of PV solar and a small wind turbine, hence the other percentage of energy generation will be compensated by a small wind turbine. The PV array size is then selected as 600 W, and it gives a daily energy output and monthly average energy production shown in Figures 4 and 5 respectively. The average daily energy output is found to be 2.6 kWh. These results were extracted from the Global Solar Atlas website.



Average hourly profles

Total photovoltaic power output [Wh]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1												
1 - 2												
2 - 3												
3 - 4												
4 - 5												
5 - 6	1									1	6	5
6 - 7	29	19	16	10	6	1	1	7	26	48	51	41
7 - 8	93	85	92	103	110	94	88	103	123	130	127	111
8 - 9	172	167	183	199	216	204	198	211	221	216	208	190
9 - 10	248	251	268	278	300	289	284	301	303	288	274	261
10 - 11	300	312	321	328	354	346	342	359	357	335	321	308
11 - 12	328	341	342	346	369	364	362	384	381	355	338	328
12 - 13	328	339	344	343	364	353	356	383	382	358	330	321
13 - 14	313	328	334	324	339	329	332	363	360	333	307	298
14 - 15	273	289	295	282	285	275	281	311	307	276	256	252
15 - 16	209	222	217	200	201	196	207	226	214	195	182	186
16 - 17	127	137	127	99	81	78	92	112	108	95	94	106
17 - 18	46	45	26	5				3	11	8	20	32
18 - 19	3	0										0
19 - 20												
20 - 21												
21 - 22												
22 - 23												
23 - 24												
Sum	2,470	2,534	2,565	2,519	2,627	2,528	2,545	2,763	2,793	2,638	2,514	2,440

Figure 4. Daily energy output.

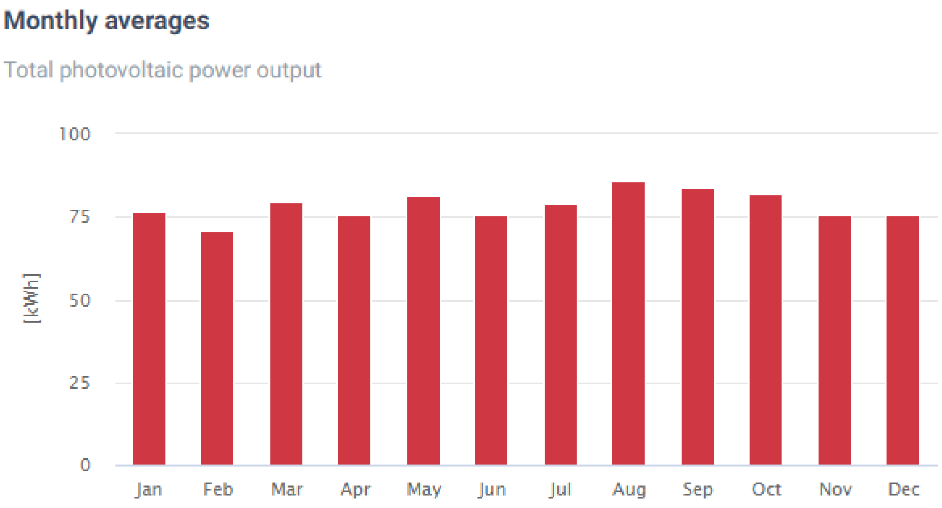


Figure 5. Monthly average energy production.

4.5. Small wind turbine sizing

A small wind turbine must compensate for the difference between daily energy demand and daily production of the PV array. The difference is found to be 0.56 kWh, which is the expected daily output that the wind energy system should provide. However, a wind turbine that will offer more than 0.56 kWh in a day is selected, this increases the reliability of the system. A 300 W wind turbine is selected and is expected to give out monthly energy of 43 kWh at an average speed of 5.8 m/s. This selected wind turbine provides more daily energy than the remainder of PV solar output. The selected location has an average wind speed of 6.41 m/s, obtained from the Global Wind Atlas website. The design and operating specifications of a wind turbine provided by the manufacturer are shown in Table 2.

Table 2. 300 W wind turbine specifications [32].

SWT-GT300 W	
Power at rated wind speed	300 W
kWh/Month @ average 5.8 m/s	43 kWh
Voltage options	12 V/24 V/8 V
Cut-in wind Speed	2.5 m/s
Rated wind speed	10 m/s
Safe wind speed	≤40 m/s
Temperature range	−40 to 60 deg
Rotor diameter	1.87 m
Swept area	2.75 meter squared
Rotor speed	600 rpm
Blade material	Aluminium alloy
Generator	3 phase PM
Rotor thrust @ 20 m/s	160 Newton
Top tower weight	17 kg

4.6. Storage devices sizing

This hybrid power system consists of two hybridized energy storage systems i.e., a battery electrochemical storage and flywheel mechanical or kinetic energy storage. These two storage devices have different operating characteristics. Electrochemical batteries are classified as medium-term storages based on their energy storage time frame while mechanical flywheel storage is classified as short-term storage [33–36]. When these two different energy storage systems are hybridized, they complement each other during the time of operation. Equation 10 can be applied to determine a battery storage capacity [37].

$$C_{bat} = \frac{E_D \times Autonomy}{DoD \times V_B} \tag{10}$$

C_{bat} is the capacity of battery storage, E_D is the daily energy demand, DoD is the allowable depth discharge of the battery, and V_B is the nominal voltage of the battery bank. Considering one day of autonomy, daily energy demand with the exclusion of high wattage appliances (kettle, microwave, and iron) which is 2.65 kWh, allowable depth of discharge of 60%, and the rated voltage of battery bank of 48 V, the capacity of battery storage is found to be 92 AH. Flywheel energy storage is also incorporated into the system and this storing device is expected to supply certain loads (high wattage appliances). Flywheel energy storage offers some remarkable advantages such as high-power density, and long life span, its life span is not affected by the number of charge/discharge cycles. However, flywheel storing device has some disadvantages such as a high self-discharge rate which affects the overall efficiency of the storage system, it is more suitable in a fixed position (it should not be moved regularly), their investment cost is high as compared to the same size of battery storage [38]. In this work, a flywheel energy storage is highly prioritized to supply high wattage loads which are intended to run for a short duration, this includes loads such as a kettle for boiling water, microwave, and electric iron. A flywheel storage system is expected to supply a maximum of two high wattage appliances at the same time. Considering a daily load profile and the peak load demand, a flywheel energy storage of 2.5 kW is considered and expected to store a minimum of 0.51 kWh in a day. Dache and Sgarciu applied Eq 11 to determine the stored energy of a rotating mass (kinetic energy) [39].

$$E_k = \frac{1}{2} I \omega^2 \tag{11}$$

E_k is the kinetic energy of a rotating mass, I is the moment of inertia, and ω is the rotating speed of a flywheel in radius per second.

5. Proposed energy utilization overview

Energy utilization scheme of this hybrid power system is based on the consumption pattern. This utilization approach allows appropriate energy sources to be assigned to fully satisfy certain load/s at the time of use (ToU) period, and the availability of power while considering a cost-energy-saving approach. A load detection system (LDS) is considered in this work, LDS assist the energy management (EM) control unit to identify the loads which are in operation. Loads are categorized into three classes: essential loads, standard loads, and high loads as shown in Table 1ToU period is divided into four different operating time slots throughout the 24 hours period as shown in Eq 12.

$$ToU = \begin{cases} Morning\ Peak, & if\ \ 5 \le t \le 9 \\ Daytime\ \ \ \ \ \ \ \ , & if\ \ 9 \le t \le 17 \\ Evening\ Peak\ , & if\ \ 17 \le t \le 21 \\ Other\ \ \ \ \ \ \ \ \ \ \ , & if\ \ 21 \le t \le 5 \end{cases} \quad (12)$$

In this study, the hybrid power system consists of four energy sources, that is a PV system, wind turbine system, battery storage and flywheel energy storage. This hybrid system is connected to the grid. Energy supervisory control is applied to control the flow of energy sources based on the assigned conditions for effective utilization of the hybrid energy at a reduced cost. Figure 6 illustrates the layout model of a proposed hybrid power system.

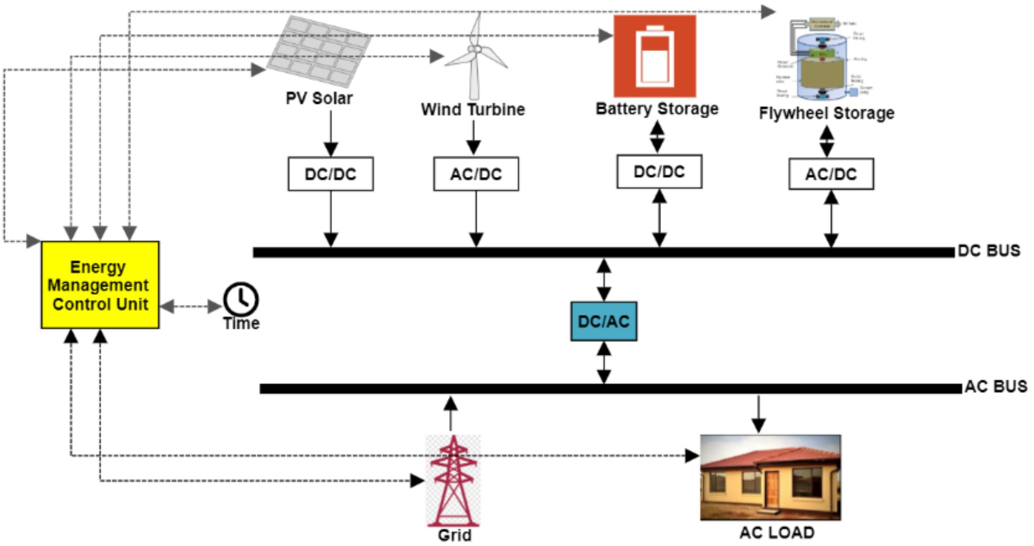


Figure 6. Hybrid power system model.

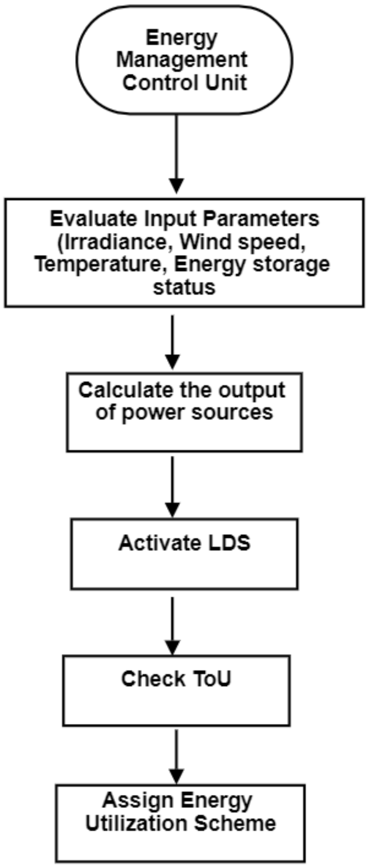


Figure 7. Energy management flowchart.

Figure 7 shows the flowchart of an energy management control unit. The proposed energy management strategy comprises the five steps outlined below.

STEP 1: Evaluating input parameters.

Input parameters such as solar irradiance, temperature, wind speed, time of use, battery state of charge, flywheel state of charge and load demand are evaluated.

STEP 2: Determining output of each energy source.

The output of each energy source is determined based on the variables of input parameters such as solar and wind energy resources, energy storage state, and load demand.

STEP 3: Detecting the load/s connected.

There are three categories of loads: essential load, standard load, and high load (highlighted in Table 1). In this phase, the system reads and detects the connected loads. This work includes a load detection system (LDS) which is user-friendly. Various load monitoring techniques have been implemented on residential applications. However, there is no current work which shows evidence of applying load monitoring technique on renewable energy technologies with the aim of inter-changing energy sources with respect to load changes. This work develops an energy utilization approach which is based on load behavioural pattern. This work considers the pre-designed non-intrusive load monitoring (NILM) which was presented by different researchers, including [8,38,40,41].

STEP 4: Checking time of use

The timeframe in which the energy is required is evaluated. Morning peak hours, day off-peak hours, evening peak hours, and late off-peak hours make up the four time periods. These time slots are separated in accordance with energy demand. This stage also plays a significant role in picking the appropriate sources to utilize identified loads and/or prioritizing essential loads based on energy availability.

STEP 5: Assigning energy source/s

Based on the calculated output of each source at time t and the kind of connected load/s at time t, the appropriate output/s of single or mixed energy source/s are assigned to satisfy the demand. Low-income houses utilize electric power for switching common loads such as lighting, fridges, kettle, iron, radio, television, and other small loads. Hence, appliances used in low-income units (households) can be controlled better as compared to the family units with a variety of appliances. There is a need to study the energy consumption pattern of an individual unit and effectively utilize hybrid energy based on the usage pattern. For an instance, the production of the solar power system might not be able to cover all the demand at some period, but it might be able to fully satisfy one of the appliances during that time of power demand.

6. Load behavioral pattern and energy utilization scheme

The energy utilization scheme is separated into four categories based on the time of day. PV solar and wind energy have distinct operating conditions, with wind energy being more effective at night based on geographical data within a particular region. Nevertheless, due to seasonal and climatic variables, wind energy systems might have a high output during the day. Load behavior categorizes energy utilization techniques based on load variations throughout various operating time intervals. First, the activities conducted at a predetermined time interval are described, and then energy sources are assigned to exchange in order to meet the demand completely.

Summary of energy utilization and energy utilization conditions for all time slots:

6.1. Load_behavior A (from 05:00 to 09:00)

The following tasks are carried out or are anticipated to be carried out between 5:00 AM and 9:00 AM.

- Essential loads such as fridge and lighting are on, but lighting is often on from 05:00 to 06:00 considering the winter period.
- A kettle is often used for a few minutes in the morning (typically for 30 or fewer minutes) to boil water.

- A microwave is used for less than 15 minutes to warm food in the morning.
- Radio is often switched on while occupants are preparing to go to work/school.
- Load demand at this time interval (05:00 to 09:00) ranges from the approximated power of 100 W to 150 W, and picks up to high demand of 1770 W in less than 20 minutes.

6.1.1. Energy utilization for load_behavior A

Condition A1: If the production of PV energy plus production of wind energy is greater than the essential load demand then PV solar and wind turbine supply essential loads.

Condition A2: If PV and wind turbine systems cannot meet the essential demand and the battery SOC is greater than SOC_{min} + 10 then:

- A battery is utilized to supply essential loads (fridge and lights) during this period, otherwise, the grid will supply the deficit.

Condition A3: If the SOC of flywheel energy storage is greater than SOC_{min} + 10 then:

- A flywheel energy system is utilized to supply high loads during this period, otherwise, the battery will supply high load demand when the SOC is greater than SOC_{min}, and the grid will supply the deficit in a case when both battery and flywheel cannot meet the high load demand.

Condition A4: If the standard loads such as radio and cellphone chargers are connected then:

- Surplus energy production of wind and PV systems are utilized to supply standard loads, otherwise, the battery will supply such loads when the SOC is greater than SOC_{min} + 20.

6.2. Load_behavior B (from 09:00 to 17:00)

The following tasks are carried out or are anticipated to be carried out between 09:00 AM and 17:00 PM.

- The fridge is on for the entire day and all lighting are off during this period.
- Standard loads such as radio, TV, DSTV, and other small loads are often not in operation at this period during weekdays and on weekends the deviation can occur since occupants will be in the house.
- The load demand at this time interval varies from an approximated power of 130 W to 208 W. High loads such as kettle, iron, and microwave are often off at this period.

6.2.1. Energy utilization for load behavior B

Condition B1: If the energy production of the PV system plus wind system is greater than the demand of essential load (fridge) then:

- PV system and wind system will supply essential load and the surplus will charge the energy storage systems.

Condition B2: If the PV system plus wind system is not enough to cover an essential load then:

- A battery system will supply deficit to essential load only when the SOC is above SOC_{min} + 20.

Condition B3: If the PV system plus wind system and the energy storage system cannot fully satisfy essential load demand, then:

- The grid will supply the deficit (the difference between hybrid power output and essential load demand).

Condition B4: If the wind system generates power at this period, then:

- The generated power will be utilized to charge the storage systems, and the surplus will be utilized to power small loads such as cellphone chargers and radio.

Condition B5: If the high load is switched on at this period (unlikely to happen regularly) then:

- The Flywheel storage system will be utilized to power high load when its SOC is above SOC_{min} + 10, otherwise, battery storage will supply when its SOC is above SOC_{min} + 10.
- During this period, the grid will only be utilized to meet essential load and high load when the hybrid energy cannot fully satisfy such load demand.

6.3. Load_behavior C (from 17:00 to 21:00)

The following tasks are carried out or are anticipated to be carried out between 17:00 PM and 21:00 PM.

- Essential loads such as fridge and lighting are ON, of note the lighting will be switched on from 18:00 upward.
- Occupants will be back from work and school, they often switch ON TV, DSTV, Radio, and cellphone chargers during this time.
- A kettle, iron, and microwave are often used for a few minutes during this period.
- The demand often ranges from the approximated power of 208 W to 300 W during this period, with a high peak of 1850 W for a few minutes.

6.3.1. Energy utilization for load_behavior C

Condition C1: If the battery SOC is greater than SOC_{min} + 10 then:

- A battery is utilized to supply essential loads (fridge and lights) during this period, otherwise, wind turbine and the grid will supply essential loads.

Condition C2: If the SOC of flywheel energy storage is above SOC_{min} + 10 then:

- A flywheel energy storage is utilized to supply high loads at this interval.

Condition C3: If the standard loads such as radio, TV, DSTV, and cellphone chargers are connected then:

- Energy production from the wind energy system will supply them aided by the battery storage.

Condition C4: If the production from the wind energy system and the stored energy cannot fully cover the essential loads, standard loads, and high loads then:

- A grid will be utilized to supply the deficit of the load demand and the production of hybrid energy.

6.4. Load_behavior D (from 21:00 to 05:00)

The following tasks are carried out or are anticipated to be carried out between 21:00 PM and 05:00 AM.

- Essential loads are switched ON at this period (fridge and lights).
- TV and DSTV are often switched on until 22:00.
- Occupants often charge their cellphones before going to sleep.
- The demand varies from the approximated power of 300 W to 208 W at this period.

6.4.1. Energy utilization for load_behavior D

Condition D1**:** If the energy production of the wind energy system is greater than the demand of essential load (fridge and lights) then:

- The wind energy system will supply essential loads and the surplus will charge the energy storage systems.

Condition D2: If the wind energy system is not enough to cover essential loads, then:

- A battery system and wind energy system will supply essential load only when the SOC is above SOC_{min} + 10.

Condition D3: If the wind energy system and the energy storage system cannot meet the demand for essential load, then:

- The grid will supply the deficit of the hybrid system and demand.

Condition D4: If the standard loads such as TV, DSTV, radio, and cellphone chargers are connected then:

- The remaining power from a wind energy system after supplying essential loads will be utilized to meet the standard load demand with the aid of battery energy storage and flywheel energy storage.

Condition D5: If the high load is switched on at this period (unlikely to happen regularly) then:

- The Flywheel storage system will be utilized to power high load(s), otherwise, a battery system and wind energy system will supply high load.
- At this period, the grid will only be utilized to meet essential loads and high loads when the hybrid energy cannot meet the demand.

6.5. Deductions and justifications of system operation

- The flywheel storage system is given priority to supply high load demand. In this system operation, high loads are often utilized for few minutes (typically less than 30 minutes in a day) and looking at the operation of a flywheel energy storage, it has a high energy density for a short discharge time.
- Battery storage system is given priority to supply essential loads during peak periods when PV solar and wind turbine cannot meet essential load demand (i.e., from 05:00 to 09:00 and from 17:00 to 21:00).
- PV energy is utilized during the day to supply essential loads and to charge the storage system. The wind energy system at this time charges the storage systems and supplies small loads which are connected.
- The production of wind energy at the selected location is often high at night, hence wind energy during this period is utilized to supply essential loads with the aid of storage systems, and if the generated energy is more than the demand then the surplus energy charges the energy storage systems.
- A grid operates as the main backup source, only utilized when the hybrid system cannot fully satisfy the demand, otherwise, a deficit will be shared by the grid.

Figures 8–11 illustrates the main flow charts for energy utilization schemes at different time of use period. The control system evaluates the status of power sources, time of use, and type of load to be served then a decision is taken to utilize certain sources at that time of load demand. These flow charts are divided into four categories (in terms of different time of use throughout the 24 hours period).

Where PV denotes photovoltaic, WT is a wind turbine, P_{PV} is the output power of a PV solar system, P_{WT} is the output power of a wind turbine, SOC_B is the battery state of charge, SOC_F is the flywheel state of charge and ES is the energy storage systems.

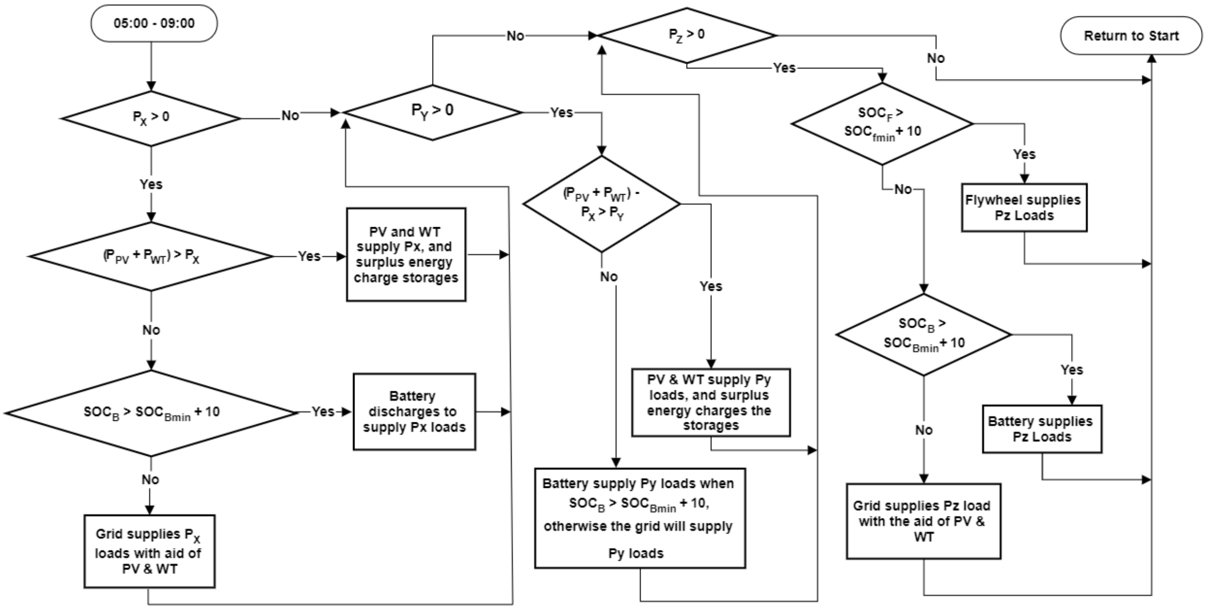


Figure 8. Utilization during morning peak-hours.

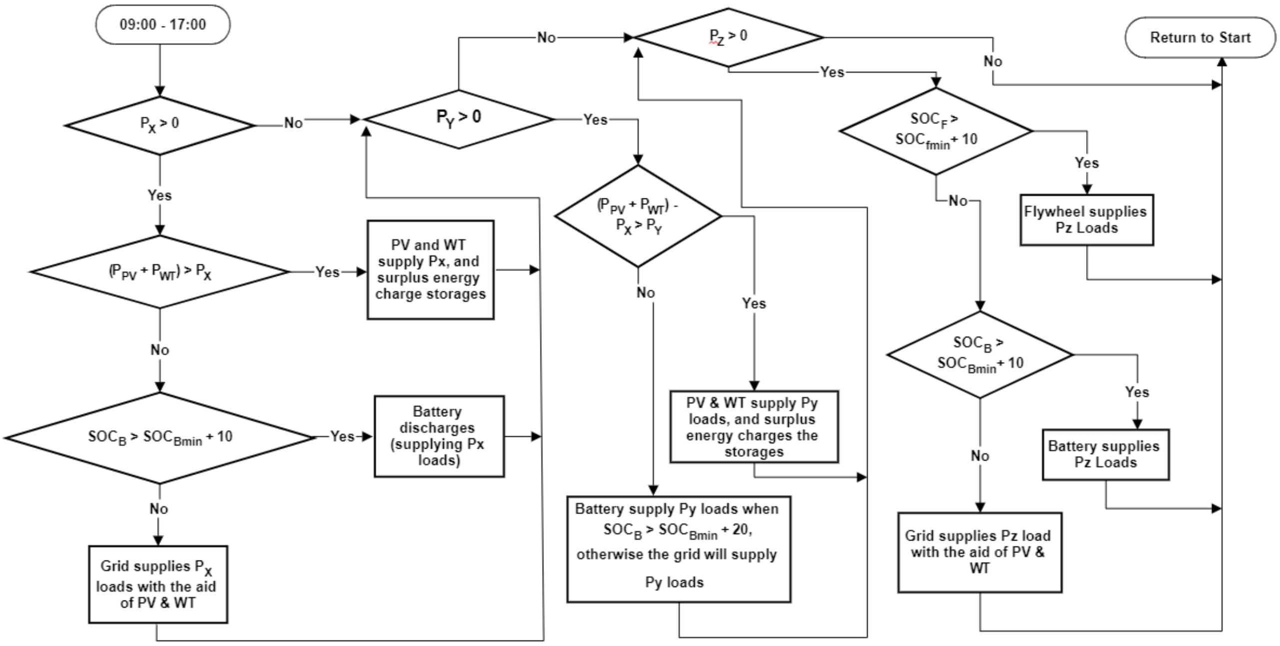


Figure 9. Utilization during daytime hours.

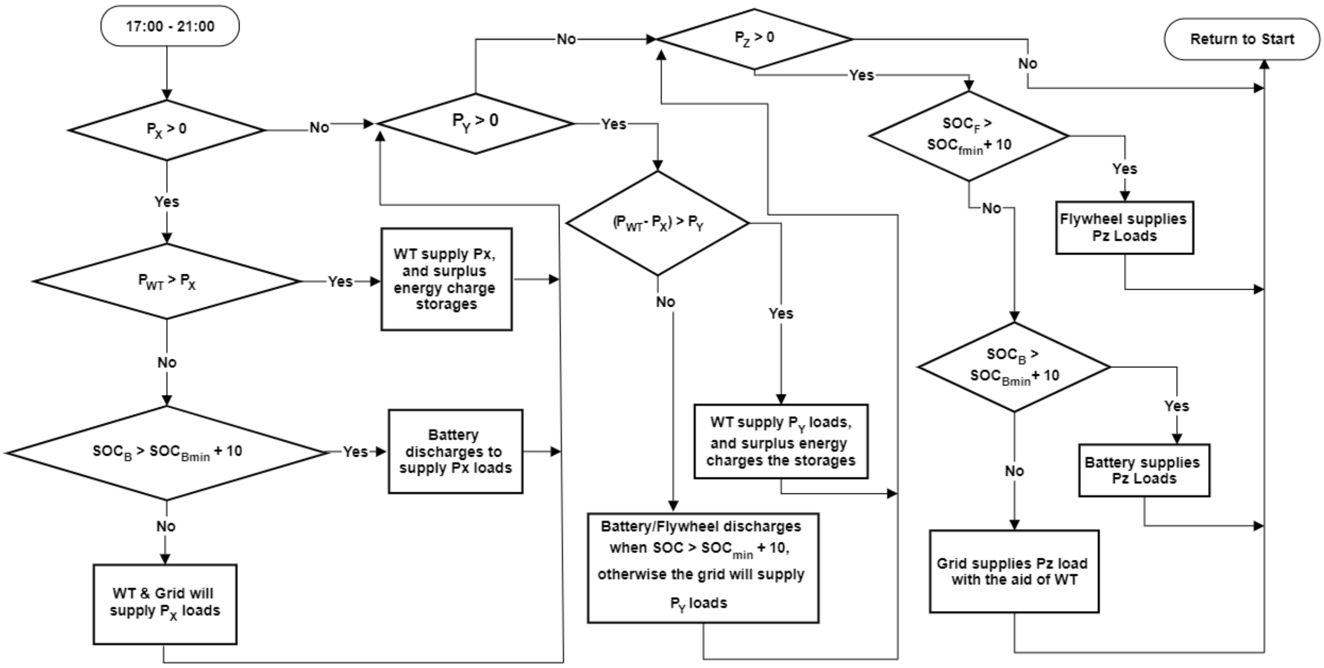


Figure 10. Utilization during evening peak-hours.

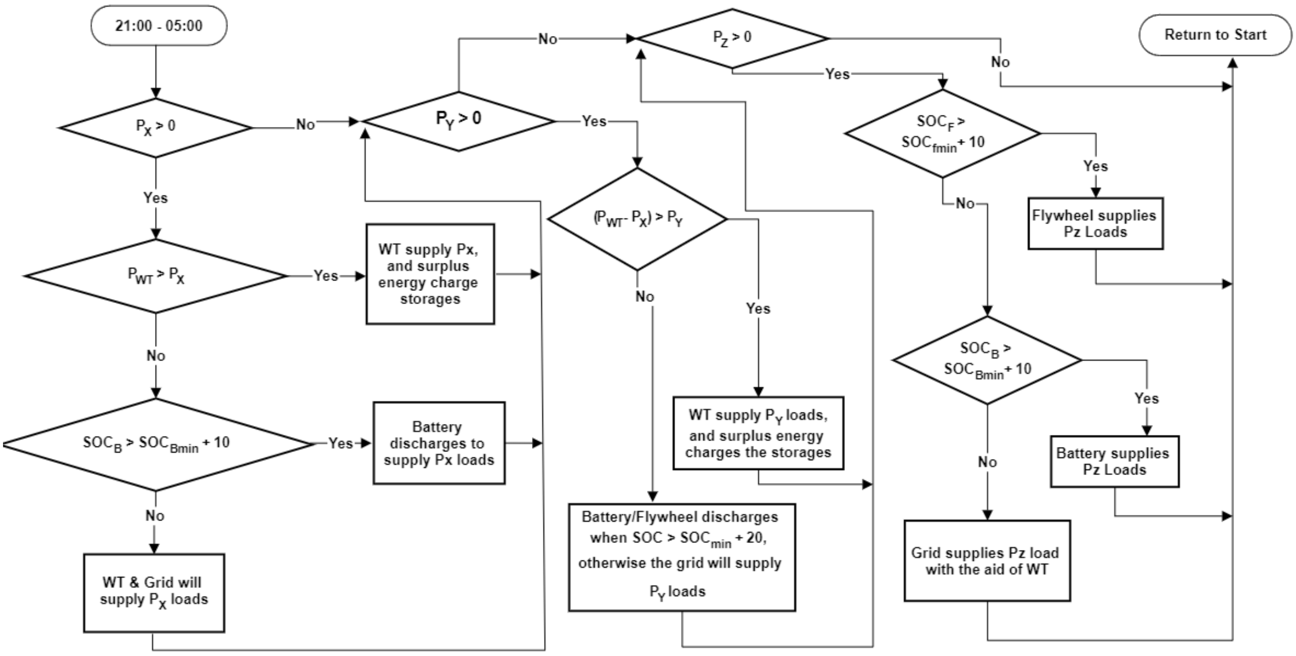


Figure 11. Utilization during late evening hours and early morning hours.

7. Simulation results

The NASA website extracts the solar and wind energy resources for a particular place. This resource is used to estimate the output of renewable energy sources over a 24-hour period with an hourly increment. To test the efficacy of the hybrid system under varying climatic circumstances, four scenarios involving fluctuations in solar irradiance and wind speed are evaluated. The status of the battery charge and flywheel is also assumed in all four scenarios. These assumptions are made to evaluate the complementarity between two storages with varying energy levels.

Each scenario is comprised of input variables collected from the NASA website (solar irradiance and wind speed), followed by the results of the computations based on the usage scheme depicted in Figures 8–11. Utilizing MATLAB to compute the utilization strategy, input variables are collected, and commands are assigned to complete computations; subsequently, the expected/anticipated outputs are calculated.

The proposed algorithm for energy management of a hybrid power system was implemented on MATLAB software. Meteorological information of a chosen location at Madimbo Village [−22.4494 30.5650 degrees] was extracted from the NASA website, these data include solar irradiance, surface temperature, and wind speed. This work considers the hybrid power system with parameters calculated and chosen in section II. The simulated results on MATLAB software are grouped into four different scenarios, and these scenarios are based on the different solar and wind resources.

Scenario 1: Months of February (High solar irradiance and medium wind speed)

Scenario 1 is when the solar irradiance is high during the day and the wind speed varies from medium to high throughout the 24-hours period and the selected month of the year is February. The irradiance and wind speed data are extracted from the NASA data access viewer. Location [−22.4494 30.5650 degrees] called Madimbo village is selected, and the extracted data are shown in Figure 12. Simulated results are shown in Figures 13 and 14.

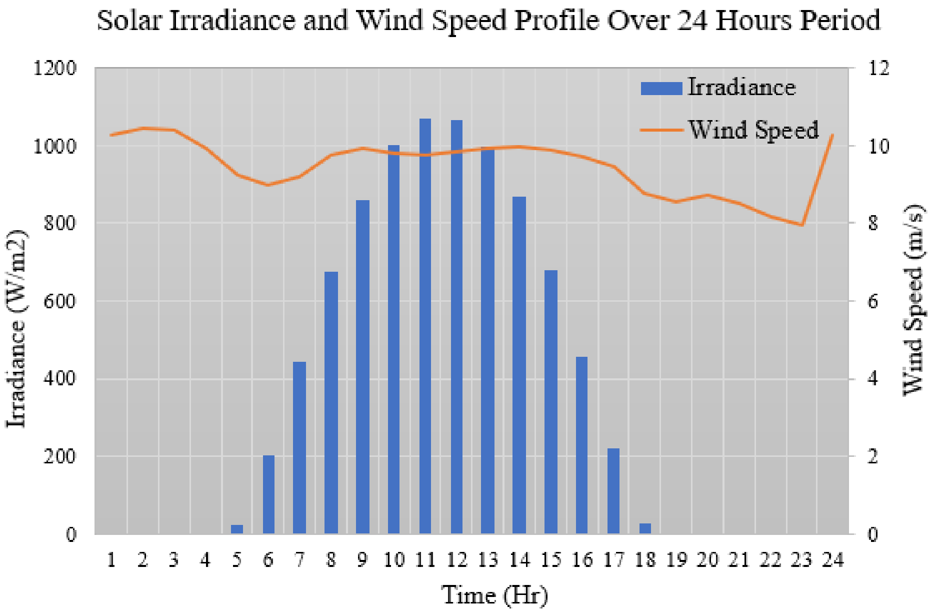


Figure 12. Solar and wind resources in scenario 1.

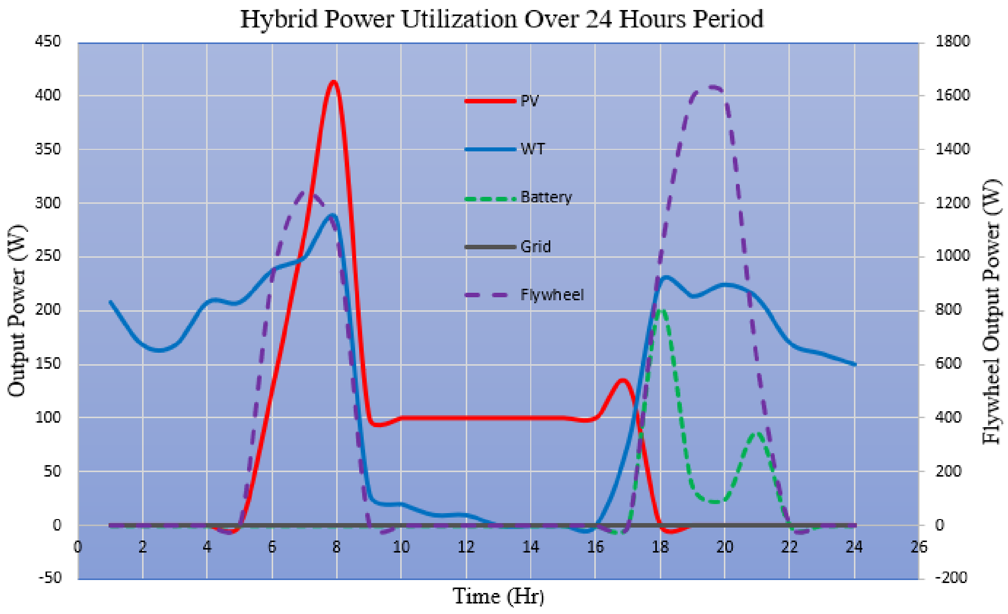


Figure 13. Power utilization in scenario 1.

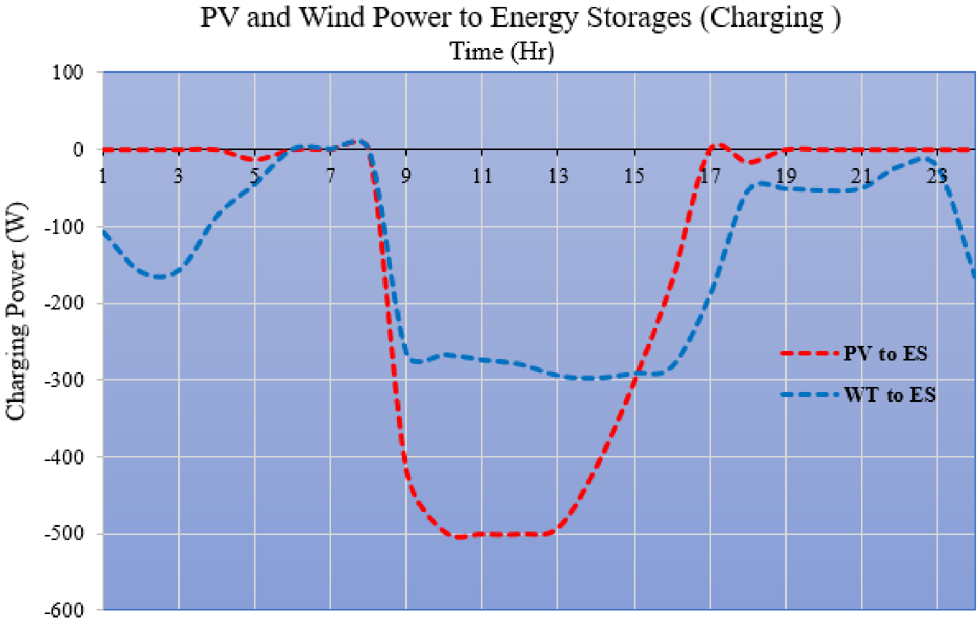


Figure 14. PV and WT extra power in scenario 1.

Figure 13 shows the contribution of each energy source over the 24-hours period in a sunny season. It can be noted from Figure 1 that both solar and wind energy generation are effectively high as their dependent variables are high. Both solar and wind energy are effectively utilized to satisfy the demand, at this moment both the flywheel and battery energy storage have enough power (SOC greater than SOC minimum), hence the flywheel energy storage is utilized to fully satisfy high amperage loads. After 17h00 the generation of solar energy edges closer to zero as the sunset and the demand starts to rise at that period, then wind energy is utilized. However, wind energy is not enough to fully satisfy all the demand, then the battery storage is supplying the deficit power, and the flywheel storage is utilized to fully satisfy high amperage loads. It can be noted from Figure 13 that flywheel energy is utilized on high amperage loads and the designated loads often come in for short periods. The grid is not utilized at this point of power utilization; therefore, it can be said that the hybrid power system fully satisfies the demand without the aid of the grid. Figure 14 shows the extra (spare) power of the solar system and wind system, these are the remaining power from the two sources after supplying the demand. This extra power is used to charge energy storage devices (battery and flywheel). However, when the energy storages are charged up to a certain level then any extra power emanating due to energy storages being fully charged is regarded as unused power.

Scenario 2: Months of February (High solar irradiance and low wind speed)

In this scenario, solar irradiance is high, but the wind speed varies from medium to low levels as illustrated in Figure 15. Both battery and flywheel energy storages are high enough to discharge (SOC greater than SOC minimum). The contribution of each energy source is illustrated in Figure 16. Due to low wind power generation, a battery is effectively utilized to assist the solar system in satisfying the demand during sun hours. Flywheel storage is utilized to satisfy high amperage loads. The solar system fully supplies the essential load (fridge) during sun hours (8h00 to 16h00) and the standard loads which are on during that period are supplied by the wind energy system. It can be seen from Figure 16 that battery energy is more utilized during peak periods (morning peak and evening peak).

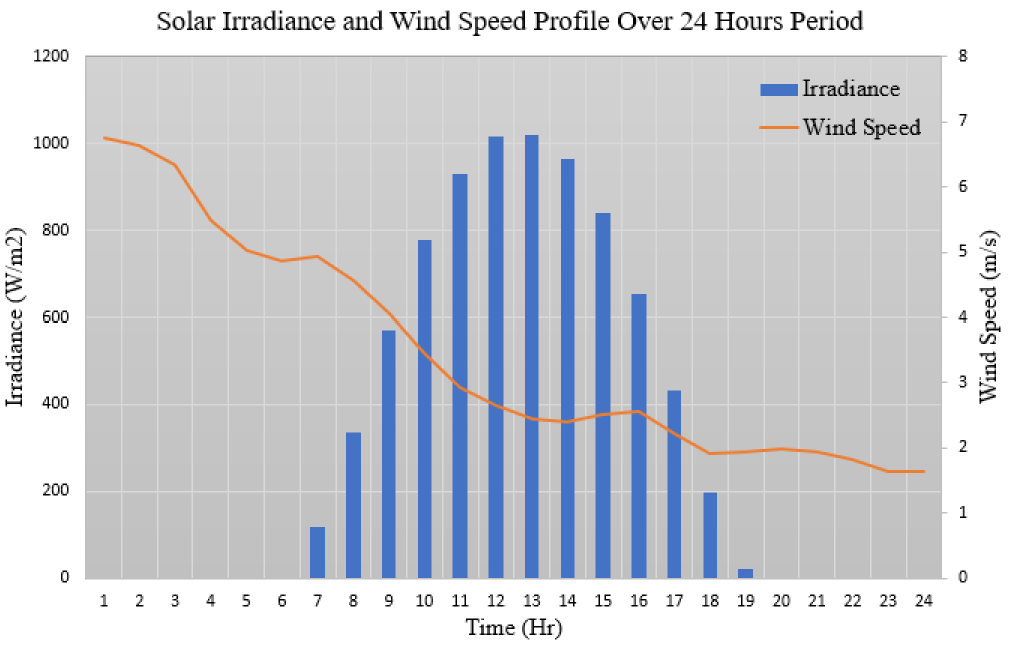


Figure 15. Solar and wind resources in scenario 2.

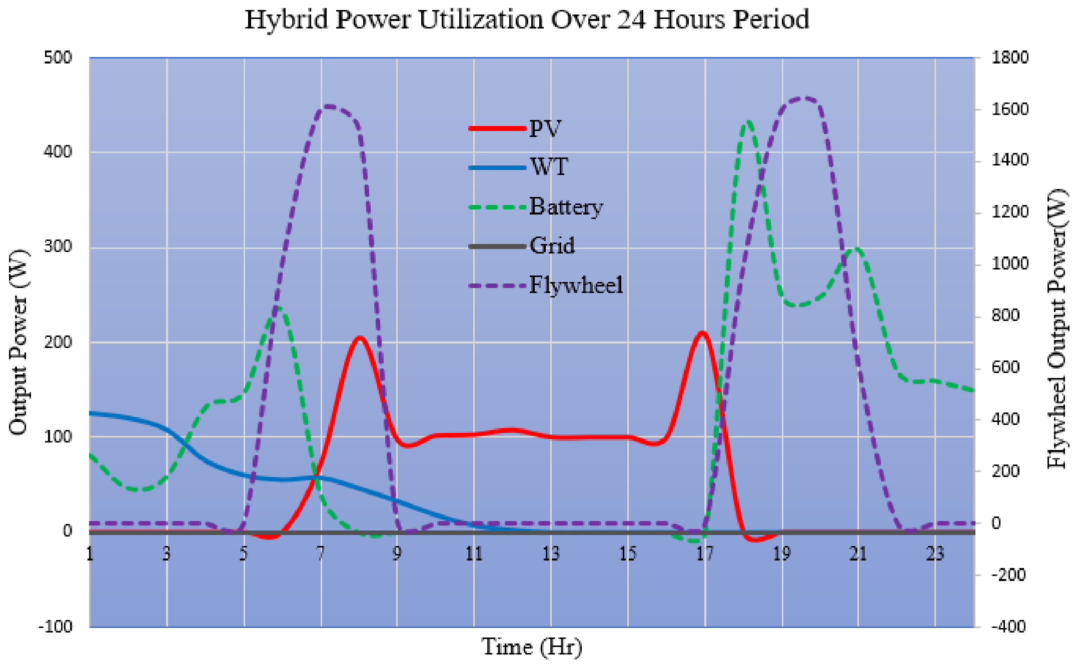


Figure 16. Power utilization in scenario 2.

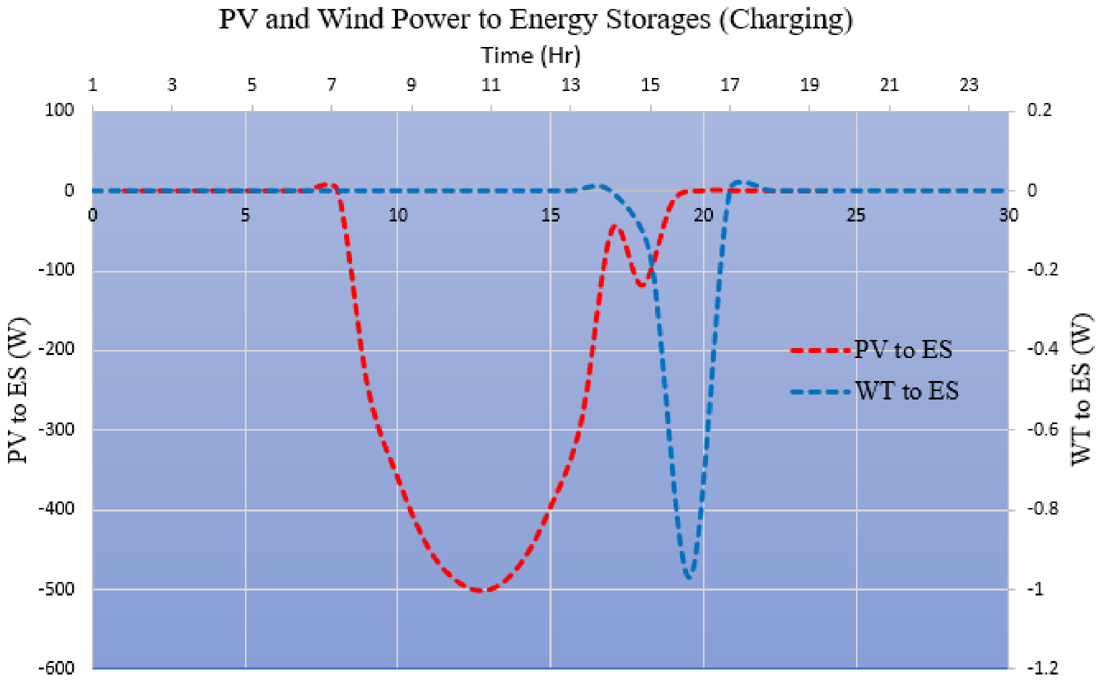


Figure 17. PV and WT extra power in scenario 2.

Scenario 3: Months of June (low solar irradiance and low wind speed)

This is scenario is based on the month of June where solar irradiance was noted to be low during sun hours, and the speed of wind varies from medium during the night to low levels during the day. In this case, both battery and flywheel energy storages are at their low state of charge (restricted from discharging power on this occasion). Weather resources are illustrated in Figure 18, while Figures 19 and 20 show the contribution of each energy source and the surplus power which charges energy storage systems, respectively. Since energy storages are at low levels, then a grid is working as the backup to supply deficit power between demand and renewable power generation. Low wind power generation is effectively utilized to supply some portion of essential loads at night, then the remaining load demand is covered by the grid. In this case, high amperage loads are supplied by the grid. Figure 20 shows the extra power from the PV solar and wind energy system. It can be noted that during sun hours, the solar system is able to supply essential load and to charge energy storage devices However, the power production of the solar system is low as compared to the first and second scenarios. Even though the grid is utilized in this case, it is more utilized on high amperage loads which are connected for a short duration.

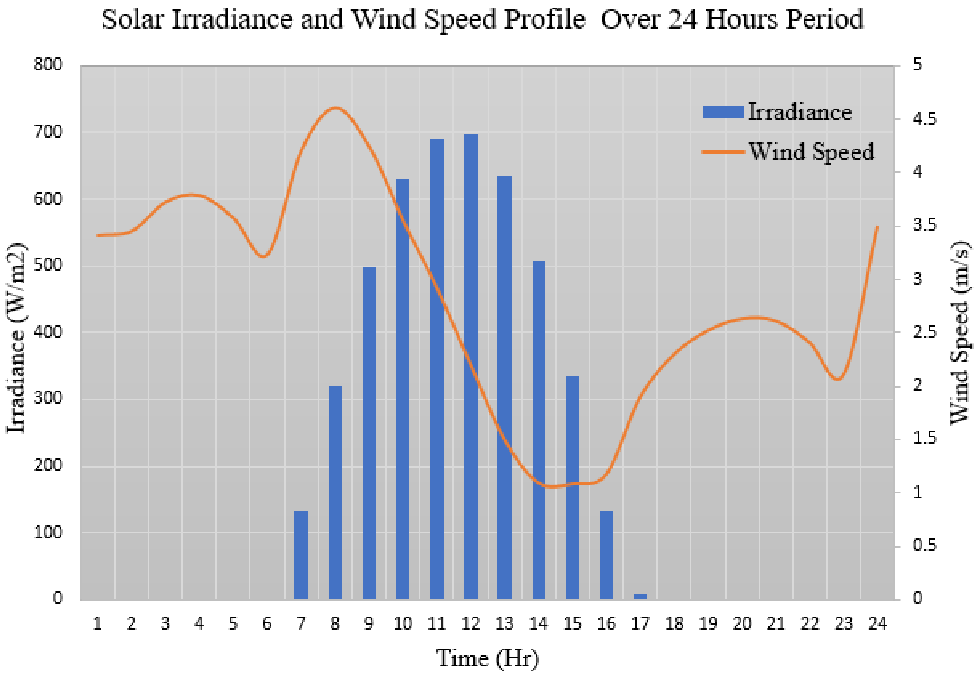


Figure 18. Solar and wind resources in scenario 3.

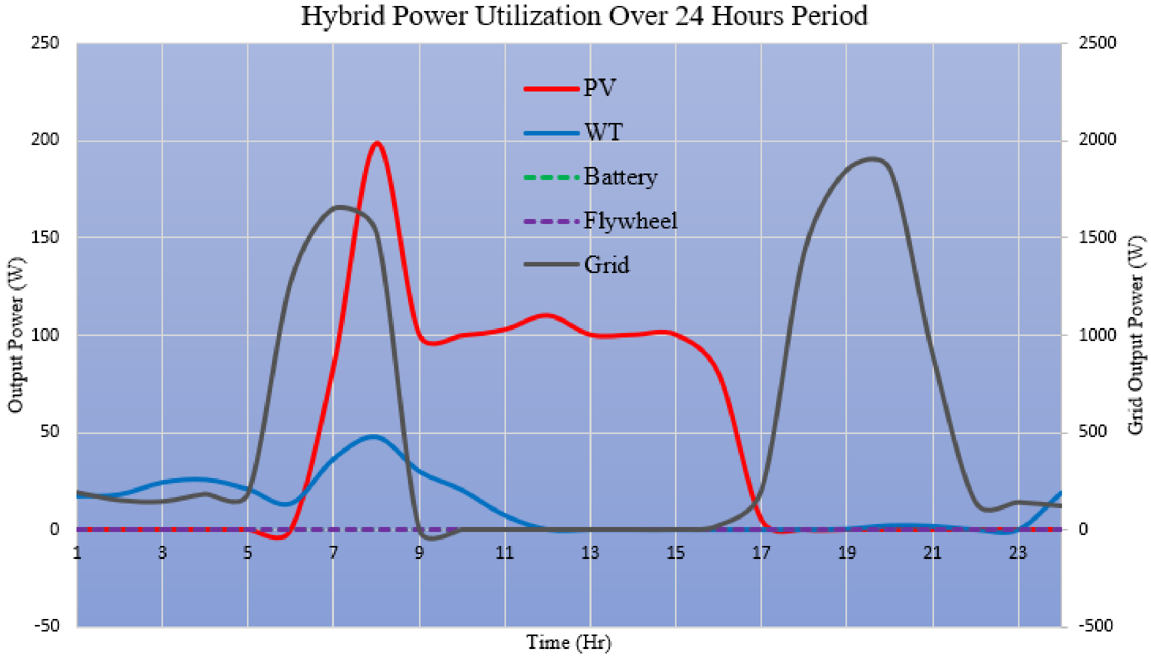


Figure 19. Power utilization in scenario 3.

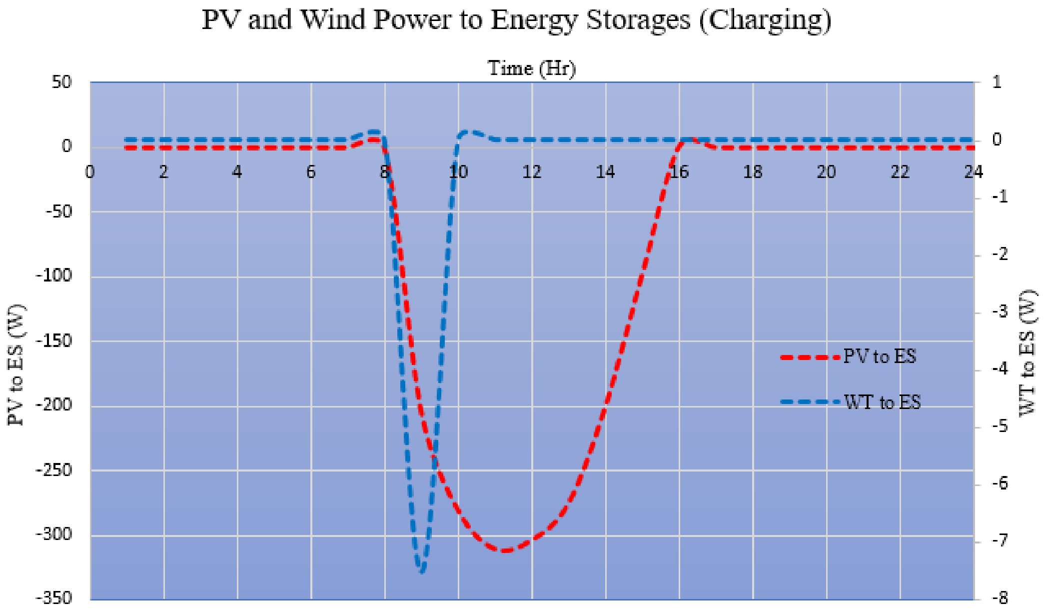


Figure 20. PV and WT extra power in scenario 3.

Scenario 4: Months of August (low solar irradiance and high wind speed)

This case is based on August month where it was depicted that wind speed is high and solar irradiance is low during sun hours. Solar and wind resources for the month of August are depicted in Figure 21. Both battery and flywheel energy storages are at high energy levels (SOC greater than 70%).

Figure 22 shows the utilization of individual energy sources, and Figure 23 shows the extra energy which is used to charge the energy storage systems. In this case, wind energy is effectively utilized to satisfy essential and standard loads during the night and, when the sunrises, the solar system is used to meet the demand based on the generated power with respect to irradiance level. In this mode of operation (during sun hours), production from wind energy is used to charge the energy storages (ES). The battery is utilized during evening peak hours and during late night hours to assist the wind system in satisfying the demand. The effectiveness of the wind energy system is high throughout the 24-hour period with the highest power generation in the evening. Flywheel is given more priority for supplying high amperage loads while battery energy storage is mostly utilized on low amperage loads.

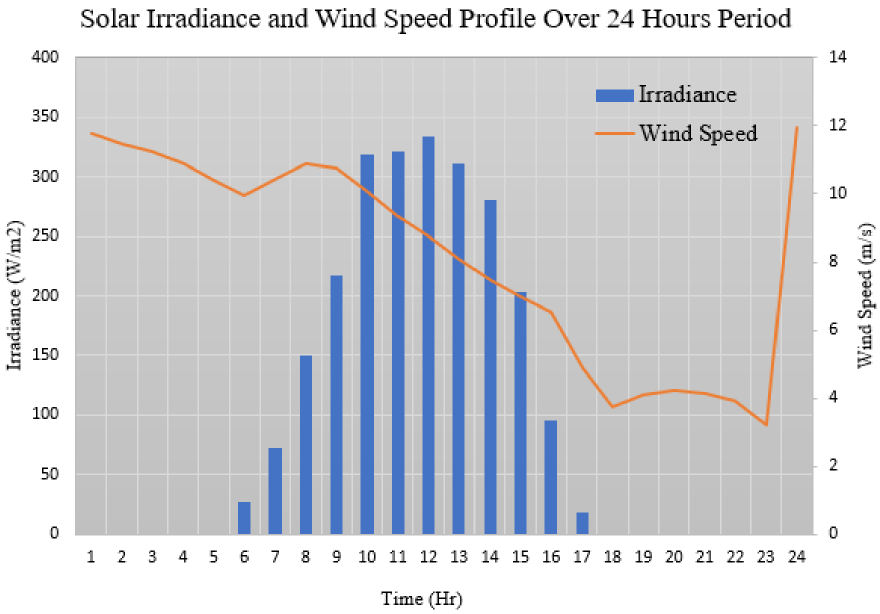


Figure 21. Solar and wind resources in scenario 4.

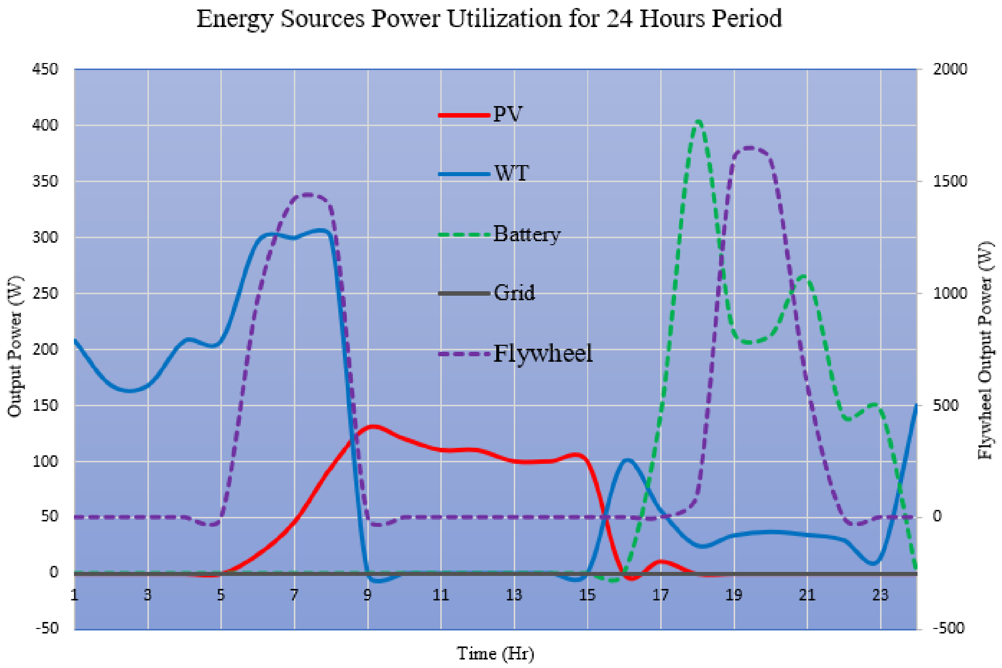


Figure 22: Power utilization in scenario 4.

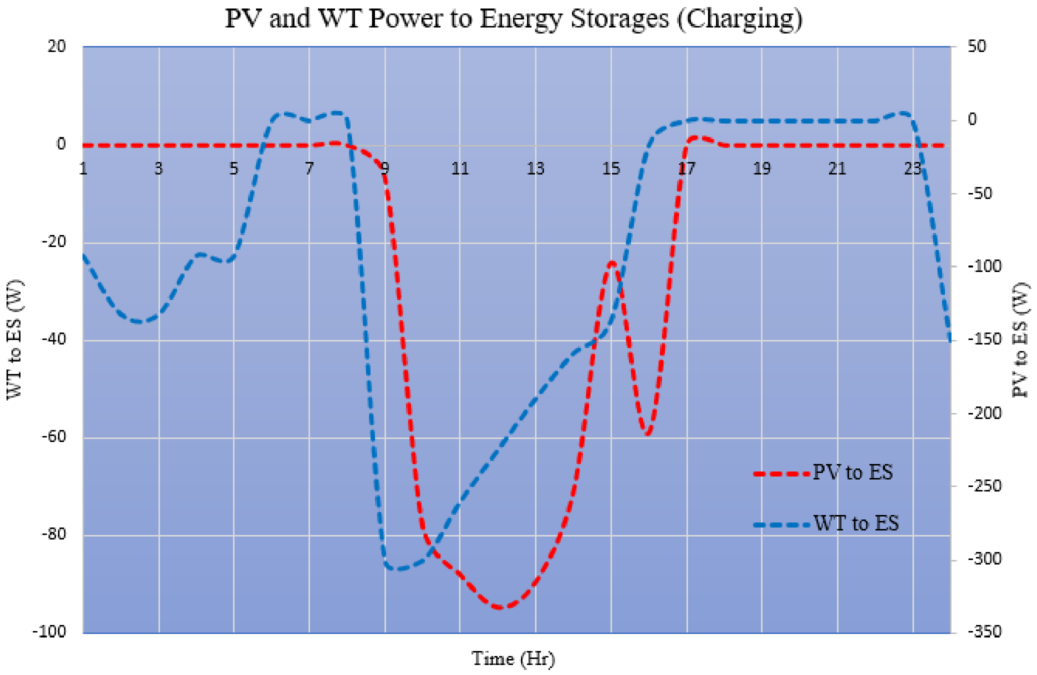


Figure 23. PV and WT extra power in scenario 4.

8. Conclusion and future work

The proposed approach shows an improvement in terms of hybrid energy utilization. The approach of utilizing hybrid energy based on consumption usage has a positive impact on reducing the size of hybrid components such as PV systems and wind energy systems. The selected household has some high amperage loads which are mostly connected for short durations, hence flywheel energy storage is assigned to fully satisfy such loads during power demand. The inclusion of a flywheel energy storage in this work cuts out the high amperage loads when sizing PV and wind energy systems, and the results show the contributions of flywheel storage for high amperage loads. To demonstrate the effect of a flywheel on a battery storage system, the full cycle equivalent method is used to evaluate battery aging [25]. Using the full cycle equivalent method, the addition of a flywheel energy storage improves the battery's health by 33.9%. Regarding this case study, the battery's expected lifespan is increased by roughly three years. The hybrid system has an investment cost of approximately $900.00 and a lower operating maintenance cost of less than $50.00. Utilizing a high proportion of renewable energy sources has reduced electricity costs by 96.7 percent. This case study focused on small households with appliances that have a low daily energy consumption, typically less than 10 kilowatt-hours. However, the developed technique for energy utilization can be improved for larger systems. The developed technique is intended to be implemented in the real world to test and validate the method's efficacy. The results show that the selected hybrid power system can fully satisfy the demand in different case scenarios with little/no aid from the grid. More utilization of renewable energy sources helps in cutting down the cost of electricity bills in the building. Furthermore, renewable energy has a positive impact in terms of saving the environment by reducing carbon footprints.

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Conflict of interest

The authors declare no conflict of interest.

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