

Design and Development of a Portable Hybrid Solar-Wind Power Generation System for Sustainable Off-Grid Applications

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ABSTRACT

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Renewable energy is a clean and sustainable alternative to fossil fuels, offering solutions to environmental and energy challenges. This research presents a portable green power generation system based on a hybrid combination of solar and wind energy. The system is designed to supply AC power for low-load applications, particularly in outdoor or off-grid scenarios. It integrates six main components: a solar photovoltaic panel, a solar panel, a micro wind turbine, a hybrid charge controller, a battery, and an inverter. The photovoltaic module captures solar radiation, while the micro wind turbine converts wind energy into electricity using a permanent magnet generator. A solar optimal panel orientation to maximize energy absorption. Energy is stored in a compact battery and managed by a hybrid controller to prevent overcharging and deep discharging. An inverter converts the stored DC power into an AC output suitable for common electrical devices. The final prototype measures, making it practical for portable use. The system achieved an efficiency of 88.38% with room for further improvement in reducing errors and enhancing energy output. This paper demonstrates the feasibility of hybrid renewable energy systems for portable applications and highlights their potential for sustainable and clean energy solutions in real-world conditions.

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1. Introduction

The excessive exhaustion of fossil fuel reserves and the intensity of environmental issues are aggravating the movement in the world towards sustainable energy sources [1]. Existential threats, in the form of increased climate variability, poor-quality air, and the rising price of fossil fuels, have revealed how important clean, accessible, and sustainable alternatives are. Solar and wind power have proved to be the most promising renewable technologies because, besides being environmentally friendly, they are able to generate power without relying on traditional grids. Such benefits are particularly important in remote areas, in disaster-prone areas, or in power-challenged locations with unreliable energy sources [2]–[3].

One of the significant problems today is to supply affordable power in places where grid electricity is not feasible or accessible. Such scenarios involve camping, field research, relief operations, and rural development programs. In such cases, transportable, again, lightweight, efficient, and energy-efficient sources of power are of enormous value. Traditional mobile generators, powered by diesel or gasoline, weigh a lot, are loud, need frequent maintenance, and cause pollution of the environment. Renewable-based portable systems are, in contrast, cleaner, quieter, and a more sustainable alternative [4]–[7].

This study introduces the application of a portable hybrid green power generation system where solar and wind energy are used to generate AC power for low-load applications. The system combines PV modules, which can be described as the photovoltaic circuit (PV), and the micro wind turbine to achieve maximum energy availability in the changing environment [8]–[11]. The solar output would tend to be more predictable during the day on clear days, but the wind could help fill the gaps during cloudy conditions and after dark [12]–[18].

Generally similar works include six primary components: a solar panel, a mini wind turbine, a hybrid controller, a battery, and an inverter. Every component is essential to the device's overall performance and effectiveness [19]–[30]. The wind stream converts its kinetic energy into electricity with the help of a permanent magnet generator installed in the wind turbine. The hybrid controller controls the charging of the battery safely and efficiently so that no overcharging or deep discharging occurs. A lightweight, high-performance battery is used to store the generated energy, and an inverter is used to convert DC electricity to usable AC power [31]–[38].

One of the major goals of this research is portability and small size. It is expected to achieve an efficient, reliable, and easy-to-transport, assemble, and operate system with a minimal set of subsystems in outdoor environments. Studies conducted at the Renewable Energy Research Unit, Polytechnic College Hawija, Northern Technical University (35.335853, 43.787203), have affirmed the feasibility of such a system for educational, recreational, and emergency applications [39]–[46], as illustrated in Fig. 1 using data from the Global Solar Atlas [47].

The paper presents the conceptual design, the selection of the components, the simulation, and the development of the hardware of the proposed portable hybrid power generator [48]–[56]. The results are evidence that renewable technology can be implemented into well-integrated solutions that have the capacity to address the increasing need for a supply of clean energy [57]–[64]. The project serves as a model for future innovations in green technology and contributes to the broader goal of sustainable energy access for all [65]–[70].

The following structure of the paper is presented. Section 2 outlines the methodology and primary calculations. Section 3 provides the process of the system design, implementation, and setup of the experiment. Section 4 shows an elaborate performance assessment, which includes an efficiency analysis. Lastly, Section 5 summarizes as well as presents the future research routes.

2. Methodology

Several stages are required to complete this research. The initial phase involves conducting literature research, utilizing the pertinent tools for this project, and disseminating and evaluating the

questionnaire. Literature evaluations must be conducted to get an understanding of solar and wind technologies [39]–[43]. Upon acquiring expertise, the design of portable green power generation utilizing hybrid wind and solar energy becomes vital [44]–[46]. Moreover, an essential understanding regarding inverters is acquired from literature reviews. Besides, the review offered invaluable information when considering inverter technology, whose influence is paramount in converting DC electricity supply harnessed by renewable sources into AC electricity. As a result, the same system can be converted to a normal 230 V AC power supply by way of a binary inverter via a three-pin plug, as shown in Fig. 2 for the hybrid system.

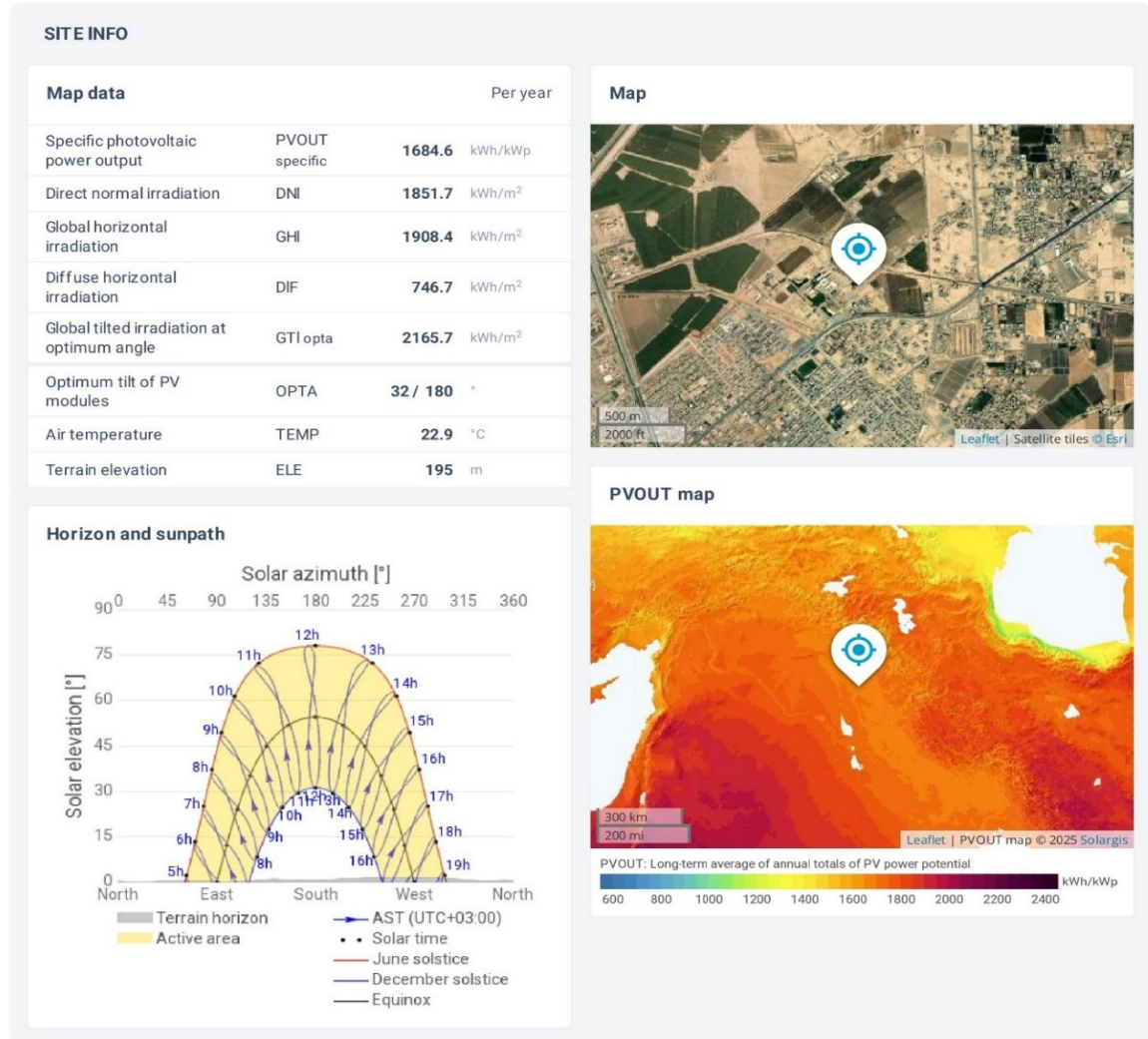


Fig. 1. Location of data from Global Solar Atlas [47]

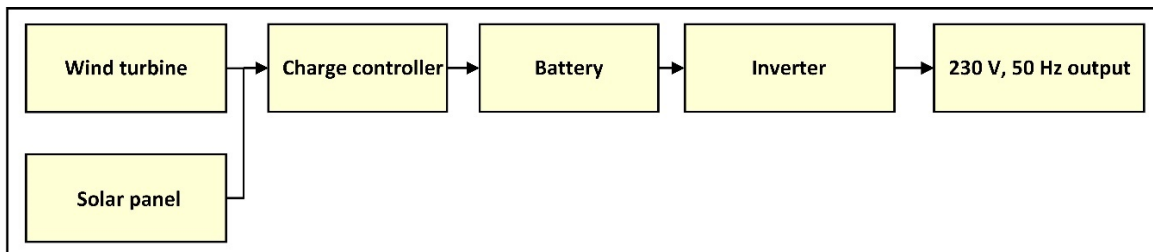


Fig. 2. Hybrid solar-wind power generation system

After carrying out a literature review, in the first step, a questionnaire will be released in order to figure out the significance of small-scale power generation and its practical implementation in

respondents' everyday routines. Per the results obtained, the grouping of the types of electrical devices most often used to conduct some outdoor activities will be determined. This step played the key role in outlining the functional requirements of the system and its relevance to real-world applications. Microsoft Excel is used in the process of processing the resultant data and calculations.

The second step is the development of the hardware model of a proposed hybrid system using the knowledge obtained during the literature review and the questionnaire analysis. The prototype uses both wind and solar energy to maximize its available energy and flexibility as the environmental conditions change. Fig. 3 illustrates a scheme of all stages of the research.

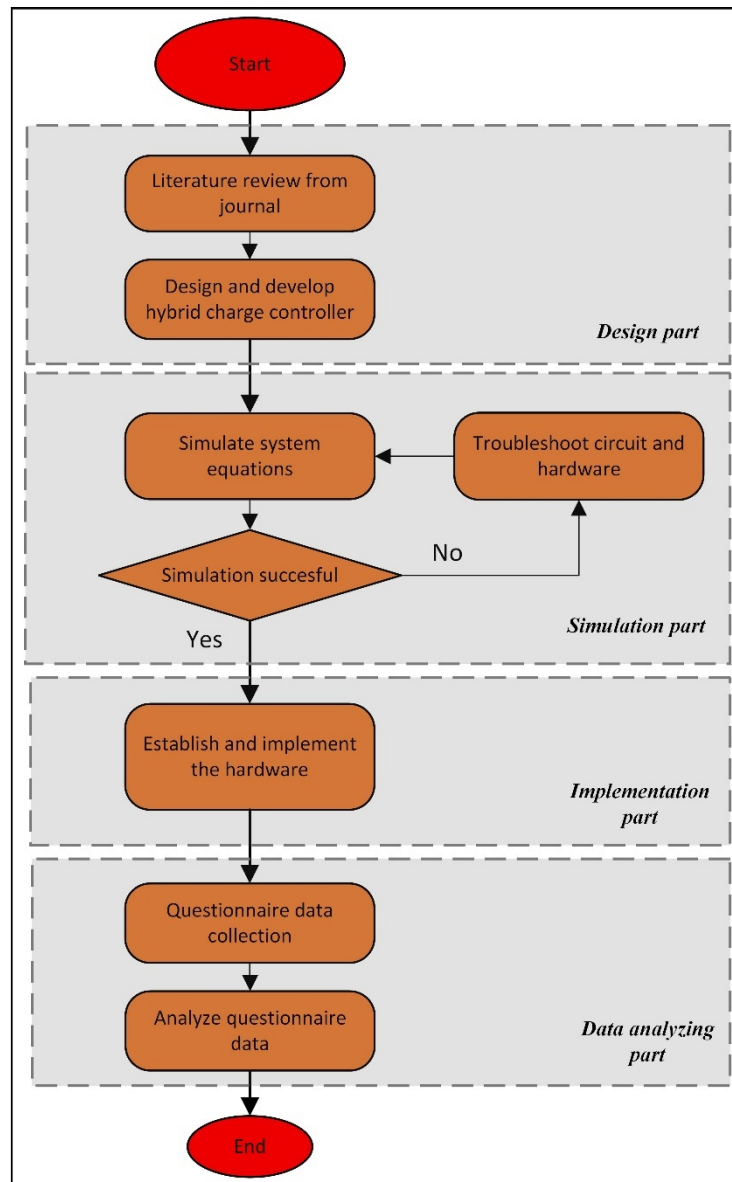


Fig. 3. All stages of the research

2.1. Solar Module Characterization

Equation (1) ascertains the size of PV modules needed in accordance with the quantity of energy that the system consumes on a regular basis and the amount of peak sunlight that is available per day.

$$P_{pv} = \frac{E_D}{S_p \eta} \quad (1)$$

Where the parameters are defined as $E_D = 26 \text{ Wp}$, $S_p = 5.43$, $\eta = 0.6$. From this calculation, the PV module rating is calculated as 7.98 Wp. Thereby, a 10Wp poly-crystalline Photovoltaic panel is chosen.

2.2. Output Current of PV

The output current generated by the PV panel can be determined using (2).

$$I_s = \frac{P_{pv}}{V_i} \quad (2)$$

Where the parameters are defined as $P_{pv} = 10 \text{ Wp}$, $V_i = 18.1 \text{ V}$. From this calculation, the output current is obtained as 0.55 A.

2.3. Battery Capacity

By using (3), the battery capacity can be determined. In this estimation, 10 hours is the time estimated to charge the battery.

$$\text{Capacity} = I_s \times T_L \quad (3)$$

Where the parameters are defined as $I_s = 0.55 \text{ A}$ and $T_L = 10 \text{ hour}$. Based on the above calculation, the best battery size is 7.6 Ah. The selection is also based on the size availability on the market.

3. Design Basis of Portable Hybrid Solar Power Generation System

Using Microsoft Visio software, the single-line diagram of the project is constructed. This single-line diagram is the guide during the installation of the component and hardware. Fig. 4 illustrates the diagram of the overall system components and connections in detail.

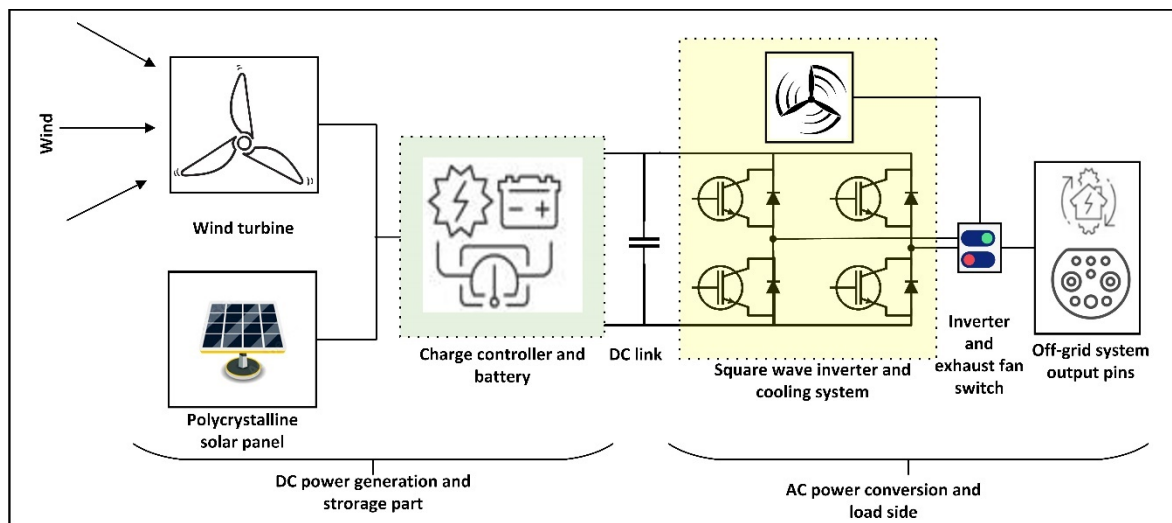


Fig. 4. Diagram of overall system components and connections

A diode is placed between the PV, wind turbine, and charge controller to make sure no feedback current can flow back through them. The forward-bias effect only allows current flow to the charge controller from the turbine and PV panel, not the other way around.

3.1. Charge Controller

This part is an essential component of wind and solar energy systems, preventing both overcharging and deep discharging of batteries. It constantly checks the battery voltage and cuts the charging source when the battery is fully charged and resumes it when the voltage drops to a specified level.

The design described in this paper is the charge controller design utilizing the NE555 timer, likely the most famous and produced combination in the history of electrical engineering, along with its billions of copies coming out annually and its availability all around the world. Fig. 5 illustrates the relationship between the active components involved in the battery charging process, while Fig. 6 displays the circuit output of the charge controller after the charging process is complete.

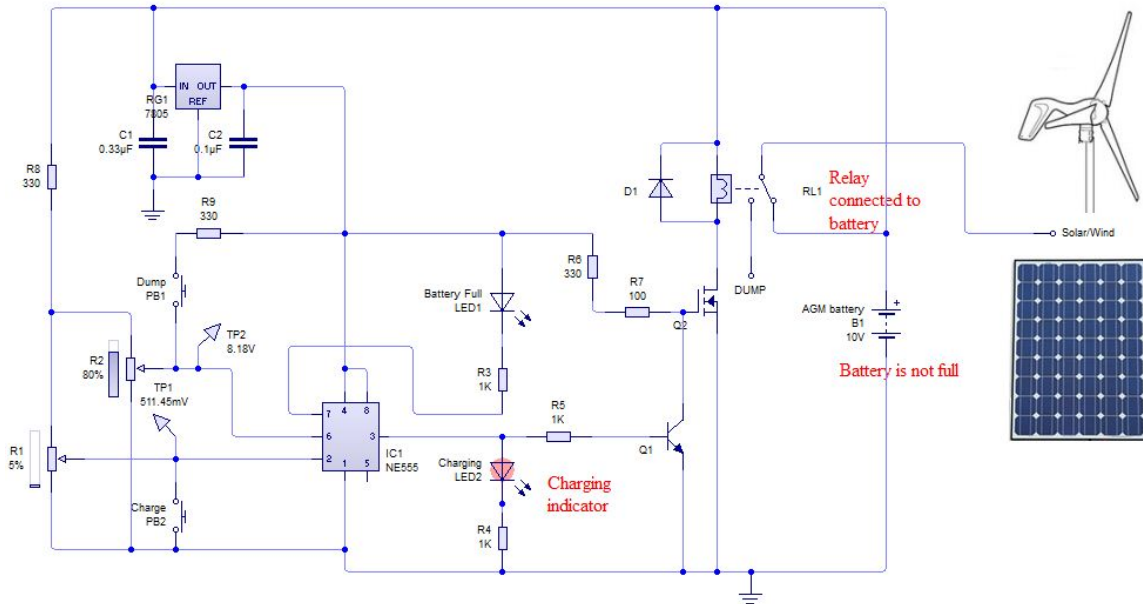


Fig. 5. State of charge controller during battery charging period

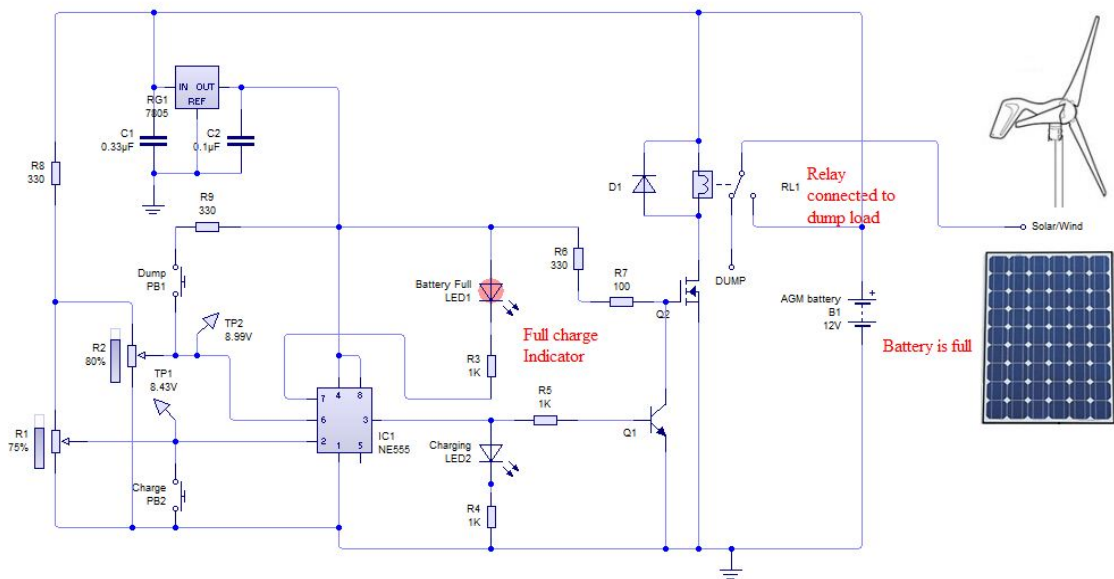


Fig. 6. State of charge controller with a fully charged battery

3.2. Wind Generator and Square Wave Inverter

This study utilizes the FD122 mini-DC generator as a wind generator. It is inexpensive, readily available, and capable of generating wind power up to 12 V and 0.3 A. A square wave inverter is utilized as a DC-AC conversion medium. The input voltage range is 10-15 V because of the unsteady wind. The inverter produces 220 V with 10% tolerance. The normal rated power of the system is 150

W. The inverter is designed to handle a maximum load power of 300 W. Therefore, it is aimed at providing the opportunity to work on higher power systems in the future.

3.3. Hybrid Solar Power Generation System

The solar system is a device attached to solar panels that follows the sun's trajectory, ensuring optimal sunlight exposure throughout the day. The output of a solar cell is maximized when it is oriented directly towards the sun, with the angle between its surface and the sun's rays at 90 degrees.

4. Experimental Results

This section will discuss the results of the research survey run. By the results, the daily power consumption, the PV panel capacity, and the required battery capacity are calculated. Furthermore, this part also explains the experimental findings of the intended portable hybrid solar power generation system, as represented in Fig. 7. The system is incorporated in realistic environmental conditions, where voltage, current, and power measurements are made at the input point in the Global Solar Atlas simulation tool. In the last step, the efficiency of the entire system and error values are assessed.

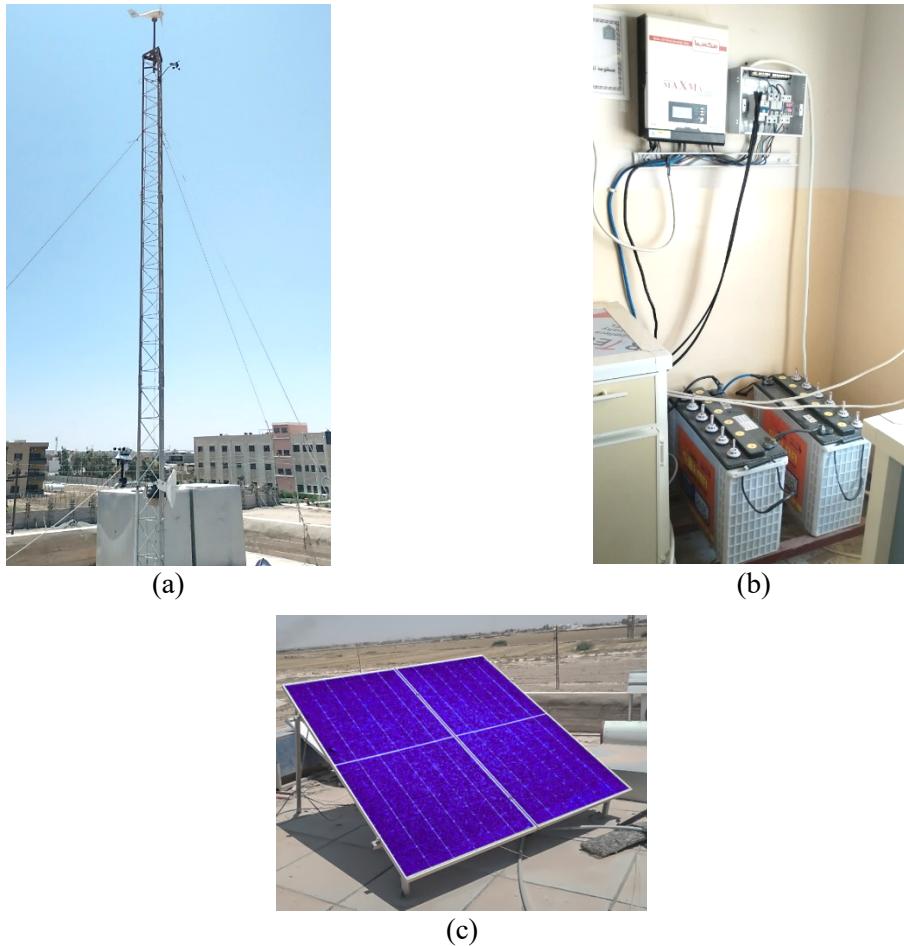


Fig. 7. Proposed portable hybrid solar power generation system

4.1. Solar Data, Wind Data, and Load Data Analysis

This questionnaire assesses the significance of the compact power supply infrastructure and its external load consumption profile. 100 random people have reacted. However, 70% have replied. From the questionnaire results, Fig. 8 presents the most vital devices: lights, fans, and electronics. The top three appliances anticipated for electrical load and radiation usage time are shown in Table 1.

Table 2 presents the total power consumption of appliances for Case 3 load conditions for nighttime before the battery is fully discharged and is derived from Table 1 for practical implementation by increasing the total power on the load side.

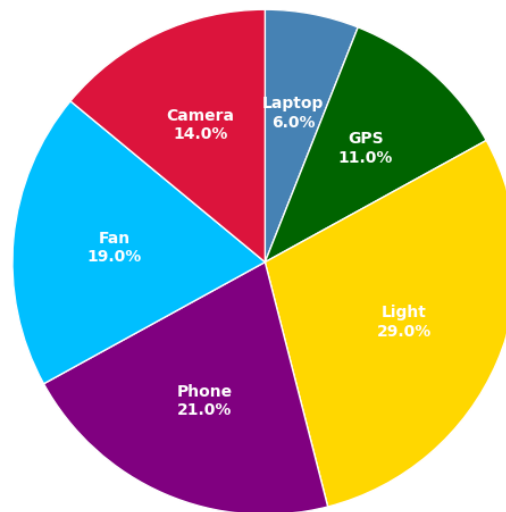


Fig. 8. Weighted percentage distribution of used devices

Table 1. Loads for Case 3 during radiation

Appliance	Power (W)	Total (Wh/day)	Utilizing (Hour/day)	Total utilization (Wh/day)
Mobile gadget	8	8	1	8
Lightbulb	6	6	1	6
Small fan	4	4	1	4
Total		18		18

Table 2. Loads for Case 3 during nighttime

Appliance	Power (W)	Total (Wh/day)	Utilizing (Hour/day)	Total utilization (Wh/day)
Mobile gadget	8	8	1	8
Lightbulb	6	6	2	12
Small fan	4	4	1	4
Total		18		26

The Global Solar Atlas program predicts daily peak radiation, whereas RETScreen predicts wind speed. Prediction location: at the Renewable Energy Research Unit, Polytechnic College Hawija, Northern Technical University. Latitude 35.335853, longitude 43.787203. The peak radiation hour generated by Global Solar Atlas Pro software is shown in Fig. 9. The average peak sun per day is determined to be 5.433 kWh/m²/d, observed too. Peak radiation hours per day are different if taken from other locations. The value of this analysis is taken from the NASA database using the Global Solar Atlas and may not be the same as the real condition [47].

Wind speed data is obtained using the RETScreen Climate Database. The location of data taken is at the Renewable Energy Research Unit, Polytechnic College Hawija, Northern Technical University. Latitude 35.335853, longitude 43.787203.

4.2. Results of Cases

Three cases are established for the presented systems. All cases are decided on during a sunny and windy day. Cases are defined as follows: In the 1st Case, the test is conducted solely on solar photovoltaic systems and wind turbines under no-load conditions. While on the 2nd case, the test is realized with a hybrid controller and the battery under no-load conditions. The 3rd case is executed to evaluate the prototype under electrical load at night utilizing a battery. The 3rd case is the final testing of the prototype to investigate whether the expected load can be supported using this portable device.

For this reason, nighttime (no radiation) is selected as the testing time to observe the hybrid controller and battery performance.



Fig. 9. Daily radiation from Global Solar Atlas [47]

4.2.1. Results of 1st Case

For this case, between 07.00 and 19.30, the readings of the multimeter are obtained. Details of the measurement of the presented system are shown in Table 3 in full. The correlated power output, using (4), could then be calculated as follows:

$$P = V_{oc} \times I_{sc} \tag{4}$$

4.2.2. Results of 2nd Case

This result is recorded concurrently with Case 1 but on a different day than the experiment itself. The hybrid controller and the battery terminal are used to obtain this result. Table 4 presents the measured power, voltages, and current at the output and input sides of the hybrid controller. For Case 2, three graphs can be obtained. It is possible to show the curve for current, power, and voltage against time.

Table 3. Results of 1st Case

Local Time	VOC (V)	ISC (A)	Utilization (Hour/day)
07.00	5.078	0.39	1.98042
07.30	7.79	0.51	3.9729
08.00	12.59	0.64	8.0576
08.30	17.72	0.77	13.6444
09.00	18.82	0.79	15.063
09.30	19.2	0.812	15.59
10.00	18.78	0.81	15.023
10.30	19.1	0.809	15.452
11.00	19.26	0.812	15.65
11.30	19.31	0.814	15.71
12.00	19.99	0.832	16.643
12.30	20.01	0.834	16.688
13.00	19.51	0.816	15.932
13.30	18.45	0.791	14.5677
14.00	18.57	0.793	14.753
14.30	18.39	0.792	14.547
15.00	18.21	0.784	14.286
15.30	18.282	0.788	14.3862
16.00	17.31	0.762	13.215
16.30	17.21	0.76	13.0625
17:00	16.618	0.742	12.349
17.30	15.53	0.71	11.0263
18.00	12.39	0.63	7.8057
18.30	10.2	0.572	5.8344
19.00	6.68	0.477	3.18636
19.30	5.101	0.302	1.5405

Fig. 10 displays the graph of voltage versus local time, and Fig. 11 illustrates the curve of current versus local time. From 07.00 until 19.30, it is virtually steady. The average voltage and current between those two times are 15.77 V and 0.713 A, respectively. At 12.30, this hybrid module produces 0.834 A and 20.01 V. After multiplying voltage and current, power is evaluated to continue the experiment analysis. The power curve is shown in Fig. 12.

**Fig. 10.** Open circuit voltage versus local time

Table 4. Results of 2nd Case

Local Time	Hybrid V (V)	DC Current (A)	DC Power (W)	Output V (V)	Output A (A)	Output Power (W)
07.00	5.23	0.3	1.569	5.15	0.29	1.4935
07.30	8.33	0.32	2.6656	8.25	0.31	2.5575
08.00	12.07	0.53	6.3971	12	0.52	6.24
08.30	12.65	0.827	10.4616	12.58	0.821	10.3282
09.00	12.36	0.815	10.0734	12.29	0.81	9.9549
09.30	12.56	0.823	10.3369	12.5	0.818	10.225
10.00	12.64	0.827	10.4533	12.58	0.822	10.3408
10.30	12.67	0.827	10.4781	12.61	0.823	10.378
11.00	12.85	0.835	10.7298	12.78	0.829	10.5946
11.30	12.77	0.832	10.6246	12.7	0.826	10.4902
12.00	12.8	0.833	10.6624	12.73	0.827	10.5277
12.30	12.39	0.816	10.1102	12.31	0.811	9.9834
13.00	12.64	0.827	10.4533	12.58	0.821	10.3282
13.30	12.96	0.841	10.8994	12.89	0.836	10.776
14.00	12.56	0.823	10.3369	12.49	0.817	10.2043
14.30	12.36	0.815	10.0734	12.29	0.809	9.9426
15.00	12.31	0.813	10.008	12.24	0.807	9.8777
15.30	12.2	0.81	9.882	12.13	0.805	9.7647
16.00	12.14	0.806	9.7848	12.07	0.8	9.656
16.30	12.07	0.803	9.6922	11.99	0.797	9.556
17:00	11.4	0.745	8.493	11.34	0.768	8.7091
17.30	11.13	0.722	8.0359	10.06	0.716	7.203
18.00	11.23	0.726	8.153	10.17	0.72	7.3224
18.30	9.3	0.69	6.417	9.24	0.69	6.3756
19.00	5.07	0.39	1.9773	5	0.39	1.95
19.30	4.223	0.29	1.2247	4	0.29	1.16

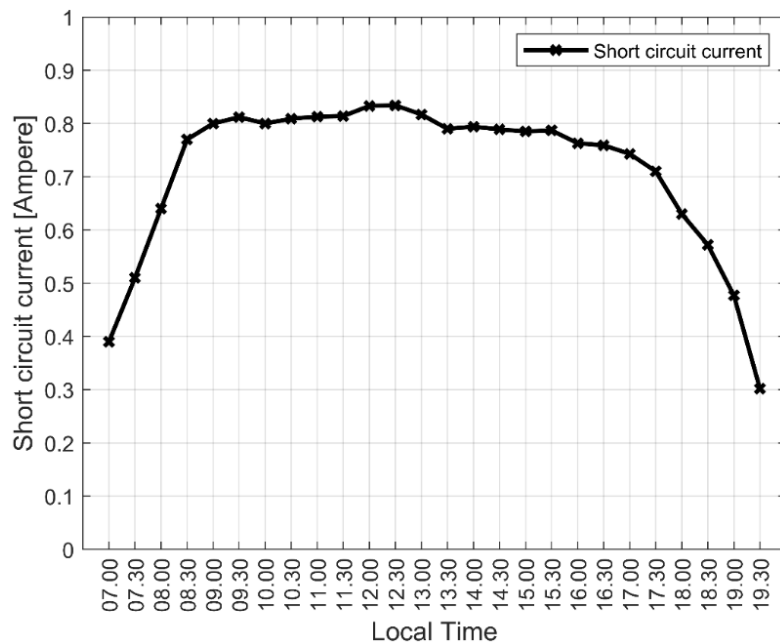


Fig. 11. Short circuit current versus local time

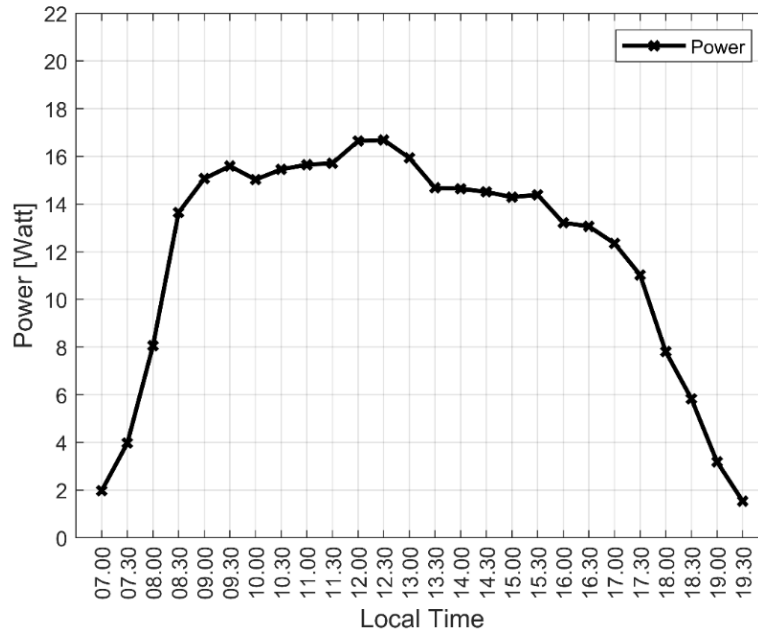


Fig. 12. Power curve versus local time

The hybrid system outputs 16.6883 W at max voltage and current. The 07.00–19.30 power average is 11.92 W. All results are somewhat different from the manufacturer's rating since sun radiation varies depending on experiment conditions, and wind speed is unfixed.

Case 2 analyzes system efficiency by integrating a solar panel, a wind turbine, an inverter, a battery, and a hybrid controller. This experiment calculates the efficiency of the presented hybrid system. Voltage and current's average values can be determined as 11.2 V and 0.72 A, taking into consideration the 07.00 to 19.30 results. Because hybrid controllers manage voltage to extend the life of the battery, the voltage dropped from 15.79 V to 11.2 V in the second trial. Case 1's current differs from Case 2's. Because solar radiation differs during the experiment.

The average value of power is calculated as 8.5 W for the hybrid component. Measured throughout the same time period. Maximum hybrid side voltage and current are 12.96 V and 0.841 A. Maximum power generated is nearly 11 W. 13.30 is the best time. Following this, average values of voltage and current are calculated as 0.714 A and 11.04 V for the load side. The average load power is 8.3 W. Fig. 13 illustrates voltage and current differences for the load side.

Current and voltage decrease 0.0055 A and 0.0747 V from 07.00 to 19.30, and it appears that the hybrid controller requires power. Based on the facts provided, (5) and (6) could assess efficiency.

$$\eta_{tracking} = \frac{P_{out}}{P_{in}} \quad (5)$$

$$\eta_{total} = \eta_{tracking} \times \eta_{conv} \quad (6)$$

With (5) and (6), efficiency of the solar system is calculated as 98.2%, and the total efficiency of the system is calculated as 88.38%. Power conversion efficiency is 90%. The inverter obtains a square wave waveform as shown below in Fig. 14. While the value V_{rms} is 230.7 V. Using a square wave inverter can save a lot of money because it is cheaper than a pure sine wave inverter. However, it is not suitable to be used for sensitive electronic equipment. It generates electrical noise and harmonics.

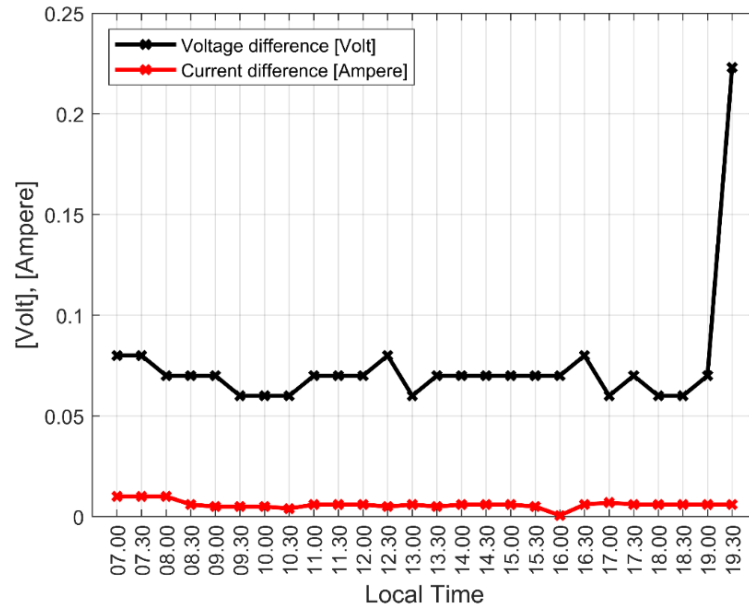


Fig. 13. Load and hybrid side's voltage and ampere differences

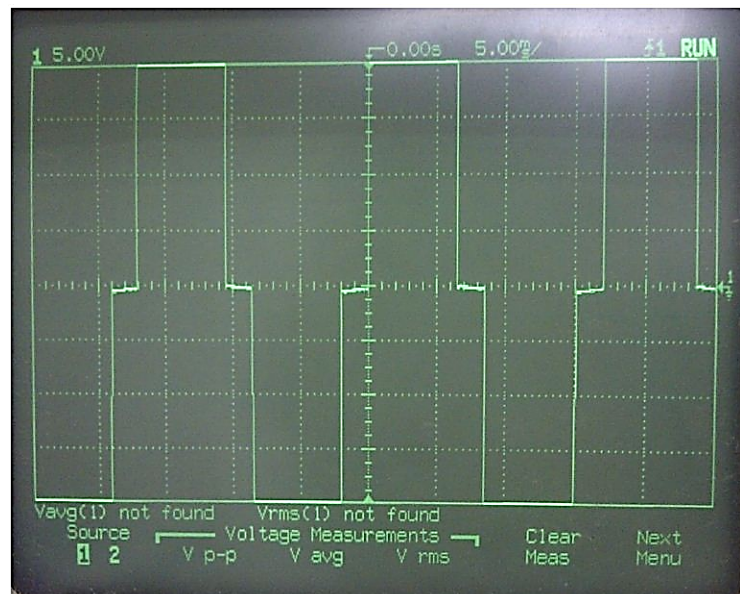


Fig. 14. Output of the inverter

4.2.3. Results of 3rd Case

Subsequent to the charging of the battery during daylight hours, this case is examined with the utilization of three appliance loads, as indicated in Table 1 and Table 2. Table 2 is the load curve for Case 3. However, Table 1 presents the loads until the battery is discharged during nighttime. Based on this result, Fig. 15 displays the comparison of Total (Wh/day) in practical and theoretical results.

5. Discussion

The creation of a portable green power generation system utilizing a combination of solar and wind energy sources signifies a substantial advancement in sustainable and accessible off-grid electricity. This study has illustrated the viability, efficacy, and advantages of integrating solar PV modules with micro wind turbines to establish a small, efficient, and eco-friendly AC power supply system. A functional prototype measuring 670 mm×390 mm×320 mm and weighing 7.5 kg has been

successfully produced through meticulous design and practical implementation. This device is designed for low-load applications for outdoor use, meeting the increasing demand for clean and portable power sources across various situations.

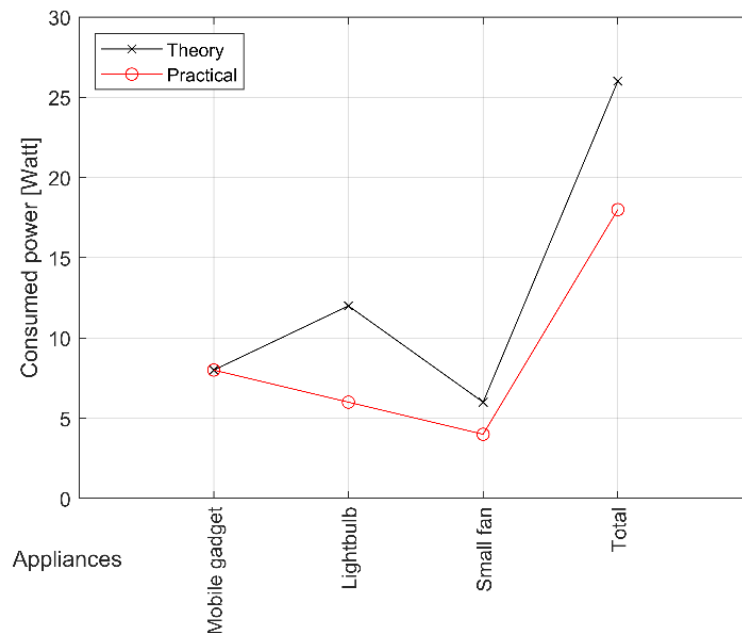


Fig. 15. Difference of practical and theoretical loads

The study commenced with an extensive examination of renewable energy technologies, emphasizing the principles and applications of solar and wind systems. Literature review and simulation tools, including RETScreen, Global Solar Atlas, and Microsoft Excel, are essential for comprehending energy generation potential, component size, and dynamics. Furthermore, student comments obtained via a structured questionnaire offered insights into the practical application and expectations of the portable gadget, affirming its significance and usability in real-world contexts.

The design has six essential components: solar photovoltaic panels, a solar panel, a tiny wind turbine, a hybrid charge controller, a battery storage unit, and an inverter. Each component is selected not only for its technical proficiency but also for its enhancement of portability, efficiency, and sustainability. The photovoltaic panels utilize solar radiation and are supported by a solar system to optimize energy collection during the day. The wind turbine, with a permanent magnet generator, enhances solar energy by supplying electricity during ideal wind conditions, especially on overcast days or at night.

The hybrid charge controller, constructed with an NE555 integrated circuit, guarantees optimal battery charging and discharging, safeguarding the battery from damage and prolonging its lifespan. The energy is stored in a tiny battery, meticulously chosen based on capacity calculations, and converted to AC power by a Vztec inverter, rendering it suitable for typical electronic devices. The inverter of the system provides a consistent 220 V AC output, appropriate for various small-scale applications in isolated or outdoor settings.

Notwithstanding its achievements, the prototype also disclosed opportunities for enhancement. The existing error rate of 44.4% indicates a necessity for enhanced control systems and precise component integration. Although efficiency is commendable at 88.38%, it can be further maximized through improved component selection and system calibration. Subsequent versions of this device could utilize thin-film solar modules to minimize dimensions and employ lighter battery technologies, such as nickel-metal hydride or lithium-ion, to decrease weight. Furthermore, integrating advanced power management systems and auxiliary power sources could improve performance and dependability under diverse environmental circumstances.

6. Conclusion

This research provides a functional model of a hybrid renewable energy device and demonstrates the feasibility of integrating sustainable energy into portable solutions. It tackles significant issues in energy accessibility, especially in off-grid or emergency situations, and aids in the overarching initiative to diminish reliance on fossil fuels. This research fosters the utilization of renewable resources in compact, practical applications, hence facilitating future advancements in accessible and impactful green technology.

This study presents a portable hybrid green power generator that demonstrates the efficacy of integrating various renewable sources into a unified system, providing dependable and environmentally sustainable electricity. With additional development and refining, this concept can transform into a commercially viable solution that addresses the increasing global demand for sustainable, portable energy solutions.

Author Contribution: All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.

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Conflicts of Interest: The authors declare no conflict of interest

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