

SMALL-SCALE HYBRID RENEWABLE ENERGY SYSTEM DESIGN FOR EDUCATIONAL APPLICATIONS: A CASE STUDY

SOHAD ABU-ELZAIT*, JOHN D. BURNS, JOSEPH C. CREWS

Department of Sustainable Technology and the Built Environment, Appalachian State
University, Boone Campus, Rm 20 Katherine Harper Hall, 397 Rivers Street, Boone, NC, USA

*Corresponding Author: abuelzait@appstate.edu

Abstract

This work presents the design process for a hybrid renewable energy system performed by students and faculty at Appalachian State University to enhance sustainability education and functionality at Caldwell Community College and Technical Institute's (CCC&TI) Watauga campus. Part of an externally funded initiative, the project promotes renewable energy awareness, hands-on learning opportunities, and stronger ties between educational institutions. The system will power an outdoor message centre at CCC&TI's new student union. Two designs are presented to offer flexibility: a cost-effective solar and battery storage system, and a more comprehensive hybrid configuration incorporating a wind turbine. The system utilises an Arduino Uno microcontroller, irradiance sensor, Morningstar SunSaver 20L charge controller, Renogy solar panels, and Primus Air 40 wind turbine. The design process involves manual calculations and performance estimates using the National Laboratory of the Rockies (NLR) System Advisor Model (SAM) modelling software. Simulation results show that the solar-only system is estimated to produce 222 kWh/year, and the hybrid system with wind is estimated to produce 451 kWh/year in total. Both designs emphasize scalability for replication at other institutions and are designed for construction by students and faculty to integrate renewable energy education into CCC&TI's curriculum. This paper focuses on phase one, involving system design and cost analysis. Phase two involves implementing the system, which will provide hands-on installation and community engagement. By bridging academic research and practical application, this project demonstrates small-scale hybrid renewable energy systems' potential to enhance education, foster community relationships, and connect institutions to the renewable energy industry.

Keywords: Battery-based solar photovoltaic system, Hands-on learning, Hybrid energy systems, Renewable energy technology education, System Advisor Model (SAM) modelling, Wind and solar power.

1. Introduction

The transition to renewable energy systems is a critical component of global efforts to reduce carbon emissions and promote sustainable development. Hybrid renewable energy systems (HRES), which combine multiple energy sources such as solar, wind, and storage, have emerged as effective solutions for decentralised power generation, especially in remote or educational settings. These systems offer improved reliability, energy autonomy, and opportunities for hands-on learning, making them ideal for integration into academic environments.

Various studies have explored the design, optimisation, and implementation of hybrid renewable energy systems (HRESs). Coelho et al. [1] developed smart hybrid systems for small energy communities, comparing stand-alone and grid-connected configurations using photovoltaic (PV), wind, and pumped hydropower storage systems. Their findings highlighted the cost-effectiveness and energy independence achievable through hybrid renewable energy solutions. Similarly, Farhat et al. [2] provided a critical review of hybrid energy systems and emphasised their growing role in residential, commercial, and institutional applications.

Recent studies have further reinforced the importance of HRESs in improving system reliability, energy security, and renewable resource utilisation. Pawar et al. [3] reviewed renewable energy hybridisation strategies and demonstrated that the integration of multiple renewable technologies and energy storage systems can improve overall system flexibility and sustainability. Nair and Garlapati [4] highlighted the benefits of hybrid wind-solar systems in reducing renewable energy intermittency and improving energy availability. Furthermore, Giedraityte et al. [5] and Khan et al. [6] identified optimisation methods, advanced control strategies, and intelligent energy management systems as key areas for improving HRES performance and long-term sustainability.

In parallel with growing adoption of renewable energy technologies, educational institutions have increasingly incorporated renewable energy systems into engineering and technology curricula. Kandpal and Broman [7] emphasised the importance of renewable energy education in preparing future engineers for the global energy transition. Similarly, Martin et al. [8] demonstrated that renewable energy laboratory platforms enhance experiential learning and student engagement, while Friman [9] further highlighted the educational value of integrating renewable energy technologies into engineering curricula as a means of exposing students to technical, environmental, and sustainability-related concepts.

Despite these advances, relatively few studies focus on small-scale renewable energy installations specifically designed for educational outreach, hands-on learning, and community engagement.

This paper contributes to the field through the development and implementation of a small-scale renewable energy platform designed to support renewable energy education, experiential learning, and community engagement. The primary contribution of this work is not the development of a novel renewable energy technology, but rather the creation of an affordable and replicable educational framework that enables students to participate in renewable energy system design, monitoring, performance evaluation, and operation. The project also serves as a visible demonstration of renewable energy technologies that promote sustainability

awareness and community engagement while providing hands-on learning opportunities in renewable energy systems.

Two alternative system configurations are evaluated: a solar-only system and a hybrid solar-wind system. The solar-only configuration is estimated to generate 222 kWh annually, while the hybrid configuration is estimated to generate 451 kWh annually. These systems provide educational institutions with practical, scalable, and cost-effective renewable energy platforms that support both instructional and community engagement objectives.

Hybrid renewable energy systems offer several advantages over single-source renewable systems, including improved reliability, resource complementarity, and greater energy availability. Solar generation is typically highest during daylight hours and summer months, whereas wind resources may continue generating power during periods of reduced solar availability. However, hybrid systems generally require higher capital investments and increased design complexity. The present study therefore evaluates both system configurations to provide educational institutions with practical and scalable renewable energy solutions.

Situated three miles away from Appalachian State University in Boone, North Carolina, is the Caldwell Community College and Technical Institute (CCC&TI) Watauga Campus. On the campus's southern side lies a hill with a view of the mountain range. This spot draws crowds in the afternoons, as people gather to witness the sunset. Adjacent to this hill is a small message board, promoting CCC&TI's educational offerings and events. The proposed hybrid energy system will be installed behind this message board (Fig. 1), creating an accessible and high visibility site for students and visitors. The system is intended to power the outdoor message centre and provide charging outlets, while serving as a practical educational resource for both students and the wider community.



Fig. 1. Caldwell Community College and Technical Institute (CCC&TI) outdoor message board and proposed system location.

Two configurations are proposed: a solar-only system, and a hybrid solar-wind system. Both configurations are designed for scalability and integration into the curriculum. The project not only enhances sustainability education but also strengthens institutional collaboration and community engagement.

The proposed system is intended to serve as a hands-on educational platform that supports instruction in renewable energy systems, electrical systems, instrumentation, and sustainability. Students can participate in system design, installation, monitoring, troubleshooting, and performance analysis activities, allowing them to apply classroom concepts in a real-world environment. The

installation also provides opportunities for undergraduate research, data analysis, and experiential learning while fostering a deeper understanding of renewable energy technologies and their role in sustainable development.

This paper aims to provide a practical reference for students and educators interested in developing similar renewable energy projects. The paper is organised as follows: Section 2 presents the design considerations, including renewable resource assessment, site constraints, and design objectives. Section 3 describes the system design process, including load analysis, component selection, monitoring system development, and implementation considerations. Section 4 presents simulation-based energy production estimates, discusses the expected performance of the proposed system configurations, and compares the proposed design with previous studies. Section 5 concludes the paper and outlines potential future developments and enhancements. Detailed cost breakdowns for both proposed system configurations are provided in Appendix A.

2. Design Considerations

2.1. Renewable resources

Boone has a strong track record in renewable energy. The Town of Boone powers all municipal buildings with renewables, and Appalachian State University has long led innovative clean energy efforts [10]. The student funded Appalachian State University Renewable Energy Initiative has installed numerous energy efficiency and renewable projects on campus, including the 100 kW Broyhill wind turbine and a 100-kW solar array at the State Farm Data Centre.

Boone, North Carolina, receives an average of 4.79 peak sun hours per day (kWh/m²/day), and an average wind speed of approximately 5 miles per hour (2.2 m/s) (Tables 1 and 2) [11-13].

Table 1. Average solar irradiance per day for Boone, NC.

Month	Daily Average Solar Irradiance (kWh/m ² /day)	Month	Daily Average Solar Irradiance (kWh/m ² /day)
Jan.	3.22	Jul.	5.96
Feb.	3.45	Aug.	5.55
Mar.	4.72	Sep.	4.79
Apr.	5.52	Oct.	4.57
May	5.53	Nov.	4.05
Jun.	5.73	Dec.	2.90

Table 2. Wind speed data for Boone, NC.

Hourly Data: Wind speed (m/s)								
Time	Mean	Min	Max	Sum	St Dev	Avg Daily Min	Avg Daily Max	
Jan	6.3	0.2	18.3	4679.6	3.4	2.2	10.4	
Feb	5.8	0.2	16.8	3905.8	3.1	2.3	8.8	
Mar	6.0	0.2	18.8	4456.2	3.4	2.4	9.2	
Apr	5.1	0.2	13.5	3670.4	2.4	1.9	8.1	
May	4.3	0.3	10.4	3229.0	2.1	2.0	6.7	
Jun	3.3	0.2	8.5	2344.3	1.6	1.3	5.3	
Jul	3.2	0.1	10.9	2359.4	1.8	1.1	5.2	
Aug	3.1	0.1	9.3	2286.6	1.5	1.4	4.9	
Sep	3.0	0.1	9.1	2139.6	1.6	1.2	4.7	
Oct	5.0	0.3	14.4	3742.2	2.4	2.2	7.8	
Nov	5.3	0.1	14.7	3850.1	2.8	2.0	8.7	
Dec	5.3	0.1	16.2	3935.1	3.2	2.4	8.0	
Total	4.6	0.1	18.8	40598.1	2.8	1.9	7.3	

2.2. Design constraints

The North Carolina Mountain Ridge Protection Act of 1983 limits construction on protected ridgelines, applying to structures above 3,000 feet or 500 feet above the adjacent valley. Watauga County follows this law and further restricts structures taller than 40 feet. Although the Act exempts windmills, this does not include modern wind turbines [14]. To comply with local codes, the turbine was therefore designed to remain under 40 feet (12.2 metres).

2.3. Design objectives

The primary objective of the proposed system is to provide sufficient renewable energy to support the outdoor message centre, lighting system, monitoring equipment, and charging outlets while serving as an educational platform for renewable energy instruction. Secondary objectives include maximising student engagement, promoting renewable energy awareness, maintaining low implementation costs, and ensuring that the design can be replicated at other educational institutions. Rather than seeking complete energy independence or minimum cost of energy optimisation, the design prioritises educational value, affordability, reliability, and hands-on learning opportunities.

3. System Design

3.1. Load analysis

The proposed renewable energy system was designed to support both operational and educational functions associated with the outdoor message centre. To improve system reliability, the electrical loads were categorised as critical and non-critical loads.

Critical loads are essential for the continuous operation of the installation and include the LED lighting system, the Arduino-based monitoring platform, the irradiance sensor, and the charge controller. These loads are expected to remain operational regardless of renewable energy availability. Non-critical loads consist primarily of student charging outlets. These loads are considered discretionary and may be temporarily reduced or disconnected during periods of limited renewable energy production. Because charging demand depends on user behaviour, both average and worst-case operating conditions were considered during system sizing.

Caldwell Community College and Technical Institute operates from 6:00 a.m. to 9:00 p.m., providing a potential 15-hour usage window for the charging outlets. Mobile device charging demand varies considerably depending on device type and charging technology. While basic charging may consume approximately 5 W [15], modern fast-charging devices may require up to 20 W. Therefore, both average (12.5 W) and maximum (20 W) charging scenarios were considered in the load analysis. The maximum-demand scenario assumes continuous operation of both charging outlets at their rated power of 20 W throughout the institution's 15-hour operating day. Although actual charging demand is expected to be lower, this conservative assumption was used to support system sizing and ensure sufficient capacity during periods of increased usage.

The LED lighting [16] load was calculated using seasonal sunset data for Boone, North Carolina. Because sunset times vary throughout the year, lighting

represents a variable load. Table 3 summarises the estimated critical and non-critical loads used for system design and sizing.

Table 3. Load analysis.

	Start	End	Total hours
CCC&TI Hours of Operation	6:00am	9:00pm	15
	Common	Average	Extreme
Phone Charger Wattage	5W	12.5W	20W
Component	Daily energy (Wh/day)		
LED message board lighting	77		
Arduino Uno controller	6		
BH1750 irradiance sensor	0.01		
Morningstar controller self-consumption	2.3		
Total critical load	85.3		
Non-critical loads (Average operating condition)			
Component	Daily energy (Wh/day)		
Two USB charging outlets ($12.5\text{W} \times 15\text{ h} \times 2$)	375		
Total non-critical load	375		
Non-critical loads (Extreme operating condition)			
Component	Daily energy (Wh/day)		
Two USB charging outlets ($20\text{W} \times 15\text{ h} \times 2$)	600		
Total non-critical load	600		

Based on the load analysis shown in Table 3, the total daily energy demand is approximately 460.3 Wh/day under average operating conditions and 685.3 Wh/day under extreme operating conditions. This corresponds to annual energy requirements ranging from approximately 168 kWh/year under average operating conditions to approximately 250 kWh/year under extreme operating conditions. The solar-only configuration is estimated to generate approximately 222 kWh/year, making it suitable for typical operation while maintaining a relatively low implementation cost of approximately \$2,296. The hybrid solar-wind configuration is estimated to generate approximately 451 kWh/year and therefore exceeds both average and extreme load scenarios, while increasing the system cost to approximately \$6,038. Importantly, both proposed configurations were designed to ensure continuous operation of the critical loads, including the LED lighting system, monitoring equipment, sensors, and control electronics. During periods of limited renewable energy availability, non-critical loads such as the charging outlets may be curtailed, while the battery storage system maintains operation of the critical loads. The additional energy production provided by the hybrid configuration further improves system resilience, accommodates seasonal variations in renewable resource availability, compensates for battery and conversion losses, and provides capacity for future educational expansion and increased charging demand. Consequently, the choice between configurations depends on institutional budget constraints, anticipated usage patterns, desired educational outcomes, and the level of operational resilience required.

3.2. Wind turbine

The turbine selection process considered two candidate options, the 12 V Primus Air 40, Fig. 2(a) and a 2-kW vertical axis turbine, Fig. 2(b). Because the system operates on a 12 V battery bank, the Primus was chosen; the vertical axis turbine only offered 24 V and 48 V configurations. Although the vertical axis model has a higher peak output, the Primus Air 40 provides a higher cut out speed and more consistent energy production as shown in the power curves (Fig. 3) [17, 18].



(a) Primus Air 40 wind turbine. (b) 2000W Vertical-axis wind turbine.

Fig. 2. Wind turbine options considered for the proposed system.

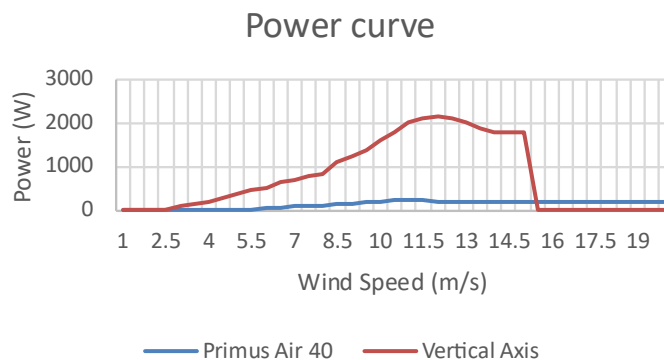


Fig. 3. Primus Air 40 and vertical axis wind turbine power curves.

Guy wires are standard for mounting small turbines and are recommended by Primus, but the limited space between the message board and the hill (Fig. 4), along with the need to preserve the view, made a concrete foundation the preferred mounting option.



Fig. 4. Space between message board and hill.

3.3. Solar panel

The panel size is selected by assessing the available roof space on the sign. The sign had a south-facing roof area of approximately 22 square feet. While one Renogy panel, in combination with the turbine, would sufficiently meet the average load requirements, the area can be optimised to fit 2 panels to meet the needs of an increased load [19].

3.4. Charge controller

Morningstar SunSaver 20L charge controller is used [20,]. Also, Primus 40 Wind Control Panel is used to optimise the wind turbine's output [21].

3.5. Battery configuration

The system utilizes a 12 V Lithium-Ion battery, Fig. 5(a) with a 3-day autonomy period, 80% depth of discharge, and a rated life cycle of 5000 cycles [22]. This battery meets the DC load voltage requirements and can be charged by the 18 V solar panels.

The 300 Ah battery capacity was intentionally selected to provide a substantial energy reserve capable of supporting the installation during extended periods of reduced solar irradiance and low wind conditions. Although the anticipated daily load requirements are relatively modest, the educational nature of the project prioritises reliability and continuous operation over strict load matching. The additional storage capacity helps maintain operation during adverse weather conditions, accommodates uncertainty in user demand, reduces battery cycling depth, and provides flexibility for future expansion of educational and monitoring functions. Furthermore, the battery bank was sized to ensure continuous operation of the critical loads, including the LED lighting system, monitoring equipment, sensors, and control electronics, even when renewable energy generation is temporarily limited.

Equipped with a Battery Management System, this battery is designed to maintain its health over time. It operates within a temperature range of 32-113°F, which suits outdoor operations. Considering Boone's extreme low-temperature record of -24 °F, the battery includes an internal heater to safeguard its performance. Additionally, an insulative battery blanket and a waterproof container will be utilized, Fig. 5(b).



(a) 12 V Lithium-ion battery.



(b) Waterproof container.

Fig. 5. Battery and waterproof enclosure.

3.6. Wire and breaker sizing

Proper wire and breaker sizing is essential to ensure safety, minimize voltage drop, and maintain system efficiency. The calculations in this section follow the 2023 National Electrical Code (NEC) and Renogy's PV wiring guidelines [23, 24]. In accordance with the National Electrical Code (NEC), all conductor and overcurrent protection sizing in this study applies a 1.25 safety factor to account for continuous operation lasting more than three hours (NEC 210.20(A), 215.3). For photovoltaic source circuits, an additional 1.25 multiplier is applied as required by NEC 690.8(A)(1) and 690.8(B)(1), ensuring adequate protection against increased current due to irradiance and temperature fluctuations.

3.6.1. Wire sizing between solar panel and charge controller

To calculate the wire size that connects the solar panel to the charge controller, Eq. (1) is used.

$$\text{Wire amp. rating} \geq \# \text{ of solar panels in parallel} \times I_{sc} \times 1.25 \times 1.25 \quad (1)$$

where I_{sc} is the short circuit current of the solar panel in amps (A), which equals 10.31 A for Renogy 175 W panel used here. The 1.25 factors account for NEC safety margins, hence for the two solar panels:

$$\text{Minimum Ampacity} = 2 \times 10.31 \times 1.25 \times 1.25 = 32.22 \text{ A}$$

$$\text{Wire Amp Rating} \geq 32.22 \text{ A}$$

According to the wire sizing chart, for 32.22 amps at 8 feet of wire, i.e. a short run (under 10 feet), 14-gauge (AWG) copper wire is sufficient to connect the solar panel to the charge controller, as it supports up to 55 A at 90°C insulation rating [24].

3.6.2. Wire sizing between charge controller and battery bank

To calculate the wire size that connects the charge controller to the battery bank and the load, Eq. (2) is used.

$$\text{Wire Amp Rating} \geq \text{Charge Controller Rated amps} \times 1.25 \quad (2)$$

Hence for the 20 A rated charge controller:

$$\text{Wire Amp Rating} \geq 20 \text{ A} \times 1.25$$

$$\text{Wire Amp Rating} \geq 25 \text{ A}$$

Accordingly, for 8 feet of wire at 25 amps, a 14-gauge (AWG) wire size is recommended to connect the charge controller to the battery bank and load.

3.6.3. Wire sizing between wind turbine and controller

The Primus Air 40 wind turbine outputs up to 40 A. Per the specifications of the Primus Wind Control Panel, 8 AWG wire will need to be ran from the turbine to the control panel [21]. This is also compliant with the NEC 310.16 guidance for this current over distances up to 20 feet [24].

3.6.4. Breaker sizing

For Overcurrent Protection Devices (OCPD) sizing we followed the NEC's "Next Size Up" rule and went from our 25A starting point to a 32A OCPD for the panel to the controller and from a 20A to a 25A OCPD for the controller to the battery [25]. Breaker sizing follows the NEC "next size up" rule as follows:

- Panel to controller: $25 \text{ A} \times 1.25 = 31.25 \text{ A} \rightarrow$ use 32A breaker.
- Controller to battery: $20 \text{ A} \times 1.25 = 25 \text{ A} \rightarrow$ use 25A breaker.

These values ensure protection against overcurrent while complying with NEC Article 690.9 and 705.60 [25].

3.7. Monitoring system

To maximise interactivity and educational value, a monitoring system that will showcase the power performance will be integrated alongside the sign. The battery system already incorporates a Bluetooth feature enabling monitoring and control through a dedicated smartphone application. This capability facilitates monitoring of the battery's condition and operational performance over its lifespan. To complement the Bluetooth functionality this system includes a data logger to monitor the output of the Primus turbine. Also, an Arduino data logger will be attached with an irradiance sensor programmed to turn the LED light on once the sun sets.

Future enhancements to the monitoring platform may include the development of a centralized web-based or desktop dashboard capable of aggregating battery status, wind turbine performance, and solar irradiance measurements into a single user interface. Such a dashboard would allow students and instructors to visualize real-time system performance, observe energy production trends, and conduct data-driven analyses as part of renewable energy education activities.

To improve educational engagement and accessibility, future versions of the system may incorporate an interactive touch-screen display located near the outdoor message board. The display could present real-time information regarding solar energy production, wind energy generation, battery state-of-charge, and environmental conditions, providing students and visitors with an intuitive understanding of system operation.

3.8. Implementation

The solar panel will be mounted onto the sheet metal roof of the sign, employing 4 Z-brackets. The roof's angle provides near-optimal positioning, so no additional angling was needed [26]. The Battery and Charge Controller will be secured in an 82-quart weatherproof container situated in the sign's roof area. Additional lumber will be added to accommodate the battery's weight.

The wiring will run through a conduit, safeguarding the system and surrounding areas. Outlets will be affixed to each signpost, and lighting strips will be positioned within the sign's glass to prevent any tampering.

3.9. Proof of concept

Last year, a hybrid system was tested on Appalachian State's campus combining a Primus Air 40 turbine (Fig. 6), a 3 kW solar array, and an 8.5 kWh battery bank.

Winds hovered just below the turbine's optimal range, but it performed well at a 7.6 m hub height. The new system will use a slightly lower 6 m hub height but with fewer obstructions. The campus tests demonstrated effective integration of the turbine with both the solar array and battery bank, and those results inform the production estimates for the local site.



Fig. 6. Primus 40 air turbine setup.

Figure 7 presents measured field data collected from a previously deployed Primus Air Silent X wind turbine. The results demonstrate the relationship between wind speed and turbine power output under actual operating conditions. As expected, power production increases with wind speed, although some variability is observed due to natural fluctuations in wind conditions and measurement uncertainty. The figure provides practical evidence that the turbine is capable of generating useful electrical power at moderate wind speeds commonly observed in the Boone, North Carolina region, supporting its suitability for small-scale educational renewable energy applications.

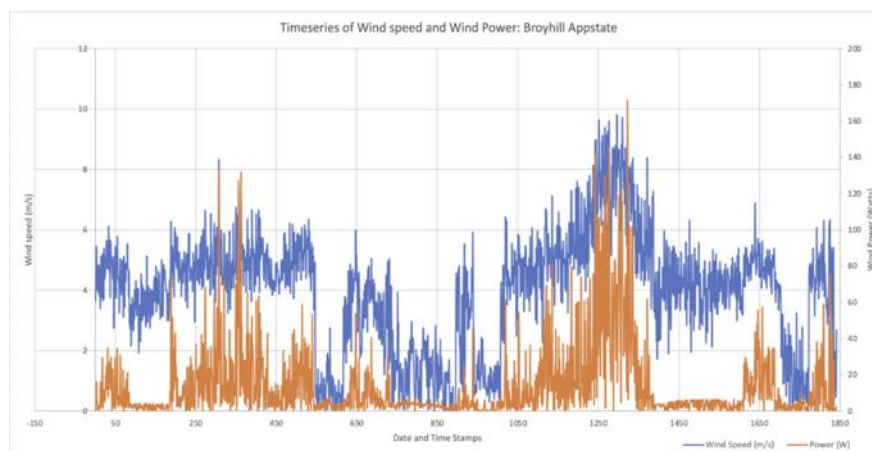


Fig. 7. Measured wind speed and power output performance of the Primus Air Silent X wind turbine.

Figure 8 illustrates the manufacturer's power curve for the Primus Air Silent X wind turbine. The curve shows that power output remains relatively low at lower wind speeds but increases rapidly as wind velocity increases above the turbine's

cut-in region. The turbine reaches its rated output at higher wind speeds and maintains stable performance across a broad operating range. Comparison of the measured field performance shown in Fig. 7 with the manufacturer-provided power curve demonstrates reasonable agreement and supports the use of the turbine for the proposed hybrid renewable energy system. Based on the average wind resource available at the project site, the turbine is not expected to operate continuously at rated power. However, it can provide valuable supplementary energy production during periods of reduced solar availability, thereby improving overall system resilience and educational value.

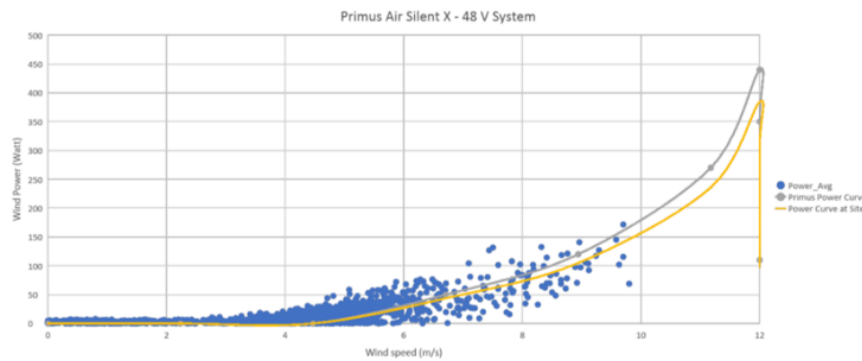


Fig. 8. Manufacturer-specified power curve for the Primus Air Silent X wind turbine.

4. System Results

This section includes monthly and annual estimates of energy production for the first year of both systems [11-13]. The estimated energy production results indicate that both proposed configurations are capable of supporting the anticipated educational loads. The solar-only configuration provides a lower-cost solution suitable for institutions with limited budgets, while the hybrid solar-wind configuration offers increased annual energy production and enhanced educational opportunities through exposure to multiple renewable energy technologies.

4.1. Energy production modelling and estimated output

The load analysis indicates annual energy requirements ranging from approximately 168 kWh/year under average operating conditions to approximately 250 kWh/year under extreme operating conditions. The solar-only configuration is estimated to generate approximately 222 kWh/year (Table 4), making it suitable for typical operation while maintaining a relatively low implementation cost of approximately \$2,296. The hybrid solar-wind configuration is estimated to generate approximately 451 kWh/year, based on the combined estimated annual production of the solar and wind systems (Tables 4 and 5), and therefore exceeds both average and extreme load scenarios, while increasing the system cost to approximately \$6,038.

Table 4. Annual solar energy production estimate

Annual solar energy production estimate	
Annual AC energy in year 1	222 kWh
DC capacity factor in year 1	14.5%

Table 5. Primus 40 estimated annual production.

Primus Air 40 production estimate	
Annual AC energy in Year 1	229 kWh
Capacity factor in Year 1	13.1%

Importantly, both proposed configurations were designed to ensure continuous operation of the critical loads, including the LED lighting system, monitoring equipment, sensors, and control electronics. During periods of limited renewable energy availability, non-critical loads such as the charging outlets may be curtailed while the battery storage system maintains operation of the critical loads.

The additional energy production provided by the hybrid configuration further improves system resilience, accommodates seasonal variations in renewable resource availability, compensates for battery and conversion losses, and provides capacity for future educational expansion and increased charging demand. Consequently, the choice between configurations depends on institutional budget constraints, anticipated usage patterns, desired educational outcomes, and the level of operational resilience required.

The specifications of the test model and the operating conditions adopted for performance evaluation are summarized in Table 6.

Table 6. Test model specifications and test conditions.

Total Annual Energy (kWh)		450.51789	
Month	Wind Energy (kWh)	Solar energy (kWh)	Monthly Energy (kWh)
January	43.575	14.2755	57.8505
February	30.9494	13.5129	44.4623
March	32.489	19.649	52.138
April	19.6879	21.4514	41.1393
May	12.6351	21.554	34.1891
June	3.25955	21.4906	24.75015
July	4.3188	22.8198	27.1386
August	2.37109	21.2533	23.62439
September	2.72665	18.0569	20.78355
October	20.3247	18.5758	38.9005
November	26.8053	16.4406	43.2459
December	29.5759	12.7197	42.2956

4.2. System diagrams

This section includes schematic diagrams for the proposed systems designs.

Figure 9 illustrates the complete hybrid solar-wind system configuration. The schematic shows the integration of the photovoltaic array, wind turbine, battery storage system, charge controller, protection devices, monitoring equipment, and electrical loads. The diagram highlights the interaction between the renewable energy sources and the shared battery bank used to support both critical and non-critical loads.

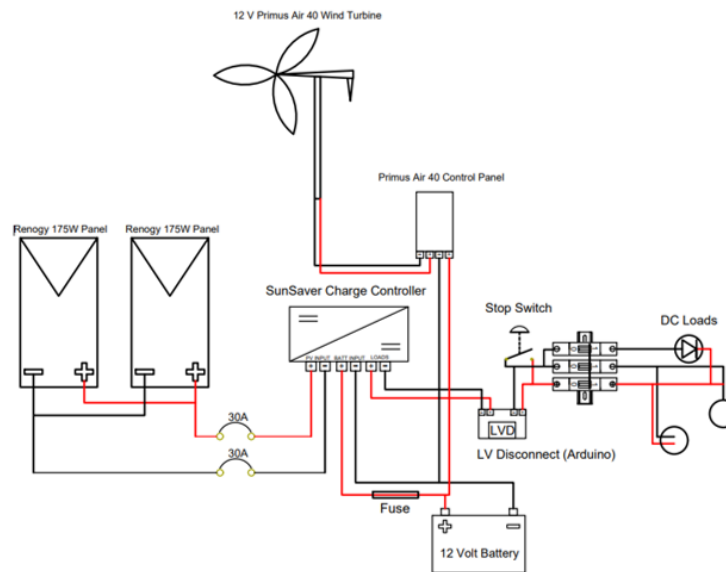


Fig. 9. Schematic diagram of the proposed hybrid solar-wind renewable energy system.

Figure 10 presents the simplified solar plus storage configuration. In this design, energy is supplied exclusively by the photovoltaic array and battery storage system, resulting in a lower-cost alternative that reduces system complexity while still supporting the intended educational functions of the installation.

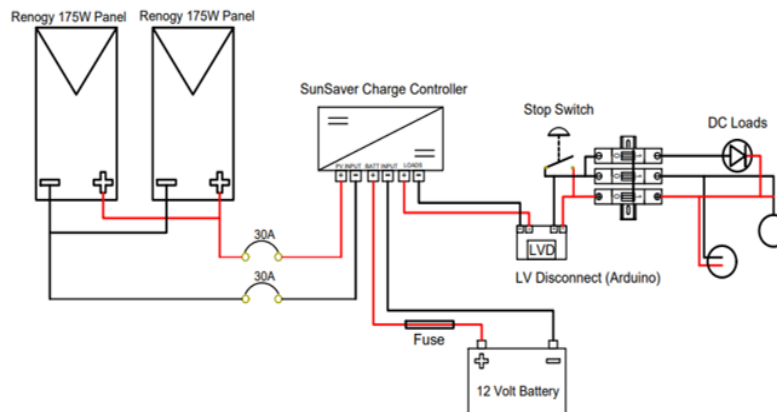


Fig. 10. Schematic diagram of the proposed solar-only and battery storage system.

The two proposed configurations provide different trade-offs between cost and functionality. The solar-only configuration offers a lower-cost solution while providing sufficient energy production for the anticipated educational loads associated with the outdoor message centre. The hybrid solar-wind configuration

increases annual energy production and improves resource diversity by combining complementary renewable energy sources. Although the hybrid system requires a higher initial investment, it provides additional educational value by exposing students to both solar and wind energy technologies. Therefore, the selection of a configuration depends on institutional budget limitations, desired educational outcomes, and renewable energy demonstration objectives. Detailed cost estimates for both proposed configurations are presented in Appendix A.

4.3. Comparison with previous studies

The proposed educational renewable energy system shares similarities with other small-scale hybrid renewable energy systems reported in the literature. Coelho et al. [1] investigated hybrid renewable energy systems combining photovoltaic generation, wind energy, and energy storage for small energy communities and demonstrated the benefits of resource diversification and improved energy autonomy. Similarly, Farhat et al. [2] highlighted the growing importance of hybrid energy systems in educational, residential, and institutional environments.

Unlike many previously reported hybrid renewable energy installations that focus primarily on energy optimisation and economic performance, the present study emphasises educational value, affordability, and hands-on student involvement throughout the design process. The proposed solar-only configuration is estimated to generate approximately 222 kWh annually, while the hybrid solar-wind configuration is estimated to produce approximately 451 kWh annually. These values demonstrate that meaningful renewable energy generation can be achieved using relatively low-cost systems suitable for deployment at educational institutions.

Furthermore, the proposed design incorporates monitoring technologies, educational engagement opportunities, and community outreach components that extend beyond traditional renewable energy system design objectives. As a result, the project serves not only as an energy generation platform but also as a practical learning laboratory for renewable energy education.

5. Conclusions and Future Work

This study investigated the design of two small-scale educational hybrid renewable energy systems. One features a comprehensive wind, solar, and storage system estimated at \$6,038, and a lower-cost solar and storage option at \$2,300. Adding a wind turbine involves an increased opportunity for community interaction and student engagement. These designs can be readily replicated at educational institutions seeking cost-effective renewable energy installations for teaching and community engagement. This work underscores the importance of championing renewable energy through education-focused initiatives.

Our hybrid system design provides an interactive renewable energy system for the students at CCC&TI. The focus in designing this system was on ensuring accessibility for students and community impact.

The system will light the outdoor message board, aiding CCC&TI in promoting upcoming events at their newly constructed student union, it will provide phone charging outlets for the students and the community, and it will serve as an educational resource for both students and the wider community.

Future development of the proposed educational renewable energy systems will focus on enhanced monitoring, automation, and user engagement. Potential improvements include the implementation of a centralized web-based monitoring dashboard that integrates battery, solar, and wind generation data into a single platform for real-time visualization and analysis.

Additional enhancements may include interactive touch-screen displays positioned near the outdoor message board to communicate system performance to students and visitors. Advanced fault detection and notification capabilities may also be implemented to automatically alert operators in the event of abnormal conditions such as low battery voltage, communication failures, or reduced renewable energy production.

Furthermore, expanding the system's long-term data logging capabilities would provide opportunities for classroom instruction, student projects, and system performance assessment. Historical operational data could be utilised to evaluate system efficiency, identify performance trends, optimise system operation, and support renewable energy research activities. These enhancements would further strengthen the educational value and practical applicability of the proposed installation.

Acknowledgement

The authors would like to acknowledge Bradley Del Vecchio for his assistance in the preparation of the system schematic diagrams used in this manuscript.

Nomenclatures

CF	Capacity factor, %
E	Energy, Wh
I_{sc}	Solar panel short-circuit current, A
P	Power, W
$\mathcal{V}$	Voltage, V

Abbreviations

AWG	American Wire Gauge
CCC&TI	Caldwell Community College and Technical Institute
DC	Direct Current
HRES	Hybrid Renewable Energy System
NEC	National Electrical Code
NLR	National Laboratory of the Rockies
NSRDB	National Solar Radiation Database
OCPD	Overcurrent Protection Device
PV	Photovoltaic
RET	Renewable Energy Technology
SAM	System Advisor Model

References

1. Coelho, J.S.T.; Pérez-Sánchez, M.; Coronado-Hernández, O.E.; Sánchez-Romero, F.-J.; McNabola, A.; and Ramos, H.M. (2024). Hybrid renewable systems for small energy communities: What is the best solution? *Applied Sciences*, 14(21), 10052.
2. Farhat, O.; Khaled, M.; Faraj, J.; Hachem, F.; Taher, R.; and Castelain, C. (2022). A short recent review on hybrid energy systems: Critical analysis and recommendations. *Energy Reports*, 8, 792-802.
3. Pawar, R.; Dalsania, K.P.; Sircar, A.; Yadav, K.; and Bist, N. (2024). Renewable energy hybridization: A comprehensive review of integration strategies for efficient and sustainable power generation. *Clean Technologies and Environmental Policy*, 26, 4041-4058.
4. Nair, K.A.; and Garlapati, N. (2024). A comprehensive review of hybrid wind-solar energy systems. *IOP Conference Series: Earth and Environmental Science*, 1372(1), 012024.
5. Giedraityte, A.; Rimkevicius, S.; Marciukaitis, M.; Radziukynas, V.; and Bakas, R. (2025). Hybrid renewable energy systems: A review of optimization approaches and future challenges. *Applied Sciences*, 15(4), 1744.
6. Khan, A.; Bressel, M.; Davigny, A.; Abbes, D.; and Ould Bouamama, B. (2025). Comprehensive review of hybrid energy systems: Challenges, applications, and optimization strategies. *Energies*, 18(10), 2612.
7. Kandpal, T.C.; and Broman, L. (2014). Renewable energy education: A global status review. *Renewable and Sustainable Energy Reviews*, 34, 300-324.
8. Martin, S.S.; Chebak, A.; and Barka, N. (2015). Development of renewable energy laboratory based on integration of wind, solar and biodiesel energies through a virtual and physical environment. *Proceedings of the 3rd IEEE International Renewable and Sustainable Energy Conference (IRSEC2015)*, Marrakech, Morocco, 1-8.
9. Friman, H. (2024). Shaping the engineers of tomorrow: Integrating renewable energies and advanced technologies in electrical and electronics engineering education. *Energies*, 17(16), 4146.
10. Town of Boone (n.d.). Renewable energy in Boone. Retrieved November 24, 2024, from <https://www.townofboone.net/461/Renewable-Energy-in-Boone>
11. National Laboratory of the Rockies (NLR) (n.d.). National Solar Radiation Database (NSRDB). Retrieved September 10, 2026, from <https://nsrdb.nlr.gov/data-sets/us-data>
12. National Laboratory of the Rockies (NLR) (n.d.). System Advisor Model (SAM). Retrieved November 24, 2024, from <https://sam.nlr.gov/>
13. National Laboratory of the Rockies (NLR) (n.d.). WIND Toolkit. Retrieved November 24, 2024, from <https://www.nlr.gov/grid/wind-toolkit>
14. North Carolina General Assembly. (n.d.). Mountain Ridge Protection Act of 1983, Chapter 113A, Article 14. Retrieved October 1, 2026, from https://www.ncleg.net/EnactedLegislation/Statutes/HTML/ByArticle/Chapter_113A/Article_14.html

15. EnergySage (n.d.). How many watts does a phone charger use? Retrieved November 24, 2024, from <https://www.energysage.com/electricity/house-watts/how-many-watts-does-a-phone-charger-use/>
16. LED Supply (n.d.). Waterproof 12V LED strip. Retrieved November 24, 2024, from https://www.ledsupply.com/led-strips/waterproof-12v-led-strip?gclid=CjwKCAjw7c2pBhAZEiwA88pOF6s_NkUQ8dILJbYYq8eSh050MyR_75pO5eFg6-kHrRvnLFwKGnSU0RoCPKIQAvD_BwE
17. Primus Wind Power. (n.d.). Air 40 Spec Sheet. Retrieved November 24, 2024, from https://www.sunwize.com/wp-content/uploads/2018/02/Primus-Air_Spec_Sheet_7-2013.pdf
18. Ubuy (n.d.). ZHIHUASMTBX 2000W vertical axis wind turbine generator. Retrieved November 24, 2024, from <https://www.global.ubuy.com/product/TZTO5VUC8-2000w-vertical-axis-wind-turbine-generator-permanent-magnet-generator-with-intelligent-controller-low-noise-helical-design-windmill-for>
19. Renogy (n.d.). Renogy 175W solar panel spec sheet. Retrieved November 24, 2024, from https://cdn.shopify.com/s/files/1/0631/0137/0483/files/RNG-175DB-H-G2_20Datasheet.pdf?v=1752029087
20. SunSaver (n.d.). SunSaver PV system controllers. Retrieved November 24, 2024, from <https://www.morningstarcorp.com/wp-content/uploads/IV-2-Morningstar-SunSaver-2026-Jun-25.pdf>
21. Primus Wind Power (n.d.). Wind control panel spec sheet. Retrieved November 24, 2024, from <https://pdf.nauticexpo.com/pdf/primus-wind-power-inc/wind-control-panel-wcp-d/66221-128930.html>
22. KiloVault HLX+ battery spec sheet (n.d.). Retrieved November 24, 2024, from <https://cdn.enfsolar.com/z/pp/2023/10/wo6f3qv0urqj2/HLX-Series-Specifications-sheet-REV-1.1.pdf>
23. Lozanova, S. (2023). GreenLancer: 2023 NEC solar code changes installers should know. Retrieved August 29, 2026, from <https://www.greenlancer.com/post/2023-nec-solar>
24. Renogy (n.d.). Sizing wires for PV systems. Retrieved August 29, 2026, from <https://www.renogy.com/learning-center/size-wire-accessory/pv-wire-options>
25. EC&M (n.d.). Sizing circuit protection and conductors – Part 1. Retrieved November 24, 2024, from <https://www.ecmweb.com>
26. Renogy (n.d.). Solar panel mounting Z bracket – Set of 4. Retrieved November 24, 2024, from <https://www.renogy.com/solar-panel-mounting-z-bracket-set-of-4/>

Appendix A

Components List and Cost Breakdown

A.1. Introduction

This section presents the cost breakdown for the two system designs described in Section 4, one including the wind turbine and one without it. A 10% labour cost and 10% contingency are added to account for market variability and to support replicability for educational use (Table A-2).

A.2. System with Wind Turbine

Table A-1. presents the cost breakdown for the system design that includes the wind turbine.

Table A-1. Solar plus storage cost (with wind turbine).

Part	Cost	Quantity	Total
Primus Air 40 Turbine	\$796.00	1	\$796.00
12V 3600 Wh Battery	\$1,125.00	1	\$1,125.00
175W Panel	\$161.49	2	\$322.98
Concrete Pad	\$500	1	\$500.00
Wind Turbine Tower	\$1,612.91	1	\$1,612.91
Wind Charge Controller	\$126.50	1	\$126.50
Solar Charge Controller	\$181.26	1	\$181.26
Emergency Stop	\$9.99	1	\$9.99
LV Disconnect	\$11.39	1	\$11.39
Arduino Uno	\$16.99	1	\$16.99
Irradiance Sensor	\$12.99	1	\$12.99
6 AWG Wire	\$0.86/foot	10	\$8.60
14 AWG Wire	\$0.14/foot	8	\$1.12
1 AWG Wire	\$2.26/foot	8	\$18.08
8 AWG Wire	\$0.56/foot	80	\$44.80
15A Wall Outlet	\$29.91	1	\$29.91
USB Wall Outlet	\$27.95	1	\$27.95
Waterproof IP65 LED Flex Strip	\$29.98	1	\$29.98
20ft of PVC Conduit	\$12.58	1	\$12.58
82 Qt Weathertight Container	\$40.60	1	\$40.60
Solar Panel Mounting Z brackets	\$15.29	1	\$15.29
15-65 Amp DC 2 Pole Circuit Breakers	\$14.99	3	\$44.97
Labour	10% of total cost	.10	\$498.99
Contingency	10% of total cost after labour	.10	\$548.89
Total Cost			6,037.77

A. 3. System without Wind Turbine (Solar Plus Storage only)

Table A-2. presents the cost breakdown for the system design that does not include the wind turbine.

Table A-2. Solar Plus Storage Cost (without Wind Turbine)

Part	Cost	Quantity	Total
12V 3600 Wh Battery	\$1,125.00	1	\$1,125.00
175W Panel	\$161.49	2	\$322.98
Solar Charge Controller	\$181.26	1	\$181.26
Emergency Stop	\$9.99	1	\$9.99
LV Disconnect	\$11.39	1	\$11.39
Arduino Uno	\$16.99	1	\$16.99
Irradiance Sensor	\$12.99	1	\$12.99
14 AWG Wire	\$0.14/foot	16	\$2.24
1 AWG Wire	\$2.26/foot	8	\$18.08
15A Wall Outlet	\$29.91	1	\$29.91
USB Wall Outlet	\$27.95	1	\$27.95
Waterproof IP65 LED Flex Strip	\$29.98	1	\$29.98
82 Qt Weathertight Container	\$40.60	1	\$40.60
Solar Panel Mounting Z brackets	\$15.29	1	\$15.29
15-65 Amp DC 2 Pole Circuit Breakers	\$14.99	3	\$44.97
Labour	10% of total cost	10	\$189.74
Contingency	10% of total cost after labour	10	\$208.71
Total Cost			\$2295.79