Journal of Intelligent Computing and Engineering
Vol. 1, No. 1, 2025, pp. 30-37
DOI:

A Hybrid Solar-Wind Power System for Sustainable Street Lighting

Ade Ananda Kurniawan
Department Of Electrical Engineering, Faculty Of Vocational Studies, Universitas Negeri Surabaya, Indonesia
e-mail address: ade.20023@mhs.unesa.ac.id (corresponding author)

Received: 16 September 2025 | Revised: 20 October 2025 | Accepted: 30 October 2025

ABSTRACT

The utilization of renewable energy as an alternative power source has become increasingly critical in reducing dependence on fossil fuels and mitigating environmental impacts. This study aims to design and implement a hybrid power generation system by integrating solar and wind energy for public street lighting applications. The system design includes the selection and integration of key components such as photovoltaic (PV) panels, wind turbines, lead-acid batteries, and charge controllers. Simulations and performance analyses were conducted to identify optimal installation sites capable of providing stable power output sufficient to meet the energy demands of street lighting. The results demonstrate that the hybrid power system can generate adequate electricity with high efficiency, ensuring reliable operation of street lights. The combination of solar and wind energy significantly enhances system stability and reliability, particularly under variable weather conditions. Furthermore, the implemented control system effectively maintains stable voltage and current output to the lighting load. This research contributes to the advancement of renewable energy technologies and their practical application in everyday infrastructure. The proposed hybrid system offers a sustainable and effective solution for addressing future energy and environmental challenges in urban and remote areas

Keywords: Hybrid Power System, Solar and Wind Energy, Public Street Lighting, Renewable Energy, Off-Grid System.

1. INTRODUCTION

The availability of electrical energy for street lighting. is a crucial aspect in developing safe, efficient, and sustainable urban infrastructure. However, conventional street lighting systems, which rely on the PLN electricity grid, often face challenges such as high operational costs, dependence on fossil fuels, and vulnerability to power outages. Furthermore, in remote areas or locations with limited electricity access, lighting provision becomes more complex [1][2][3][4]. Therefore, alternative solutions are needed that are self-sufficient, environmentally friendly, and economical in the long term. Renewable energy, particularly solar and wind energy, offers significant potential as alternative energy sources for street lighting systems. These two sources are complementary: solar energy is optimal during the day, while wind energy is often more consistent at night or during cloudy weather [5][6][7]. By combining these two sources in a single system, hybrid power plants can provide a more stable and reliable electricity supply, even in unpredictable weather conditions. Hybrid systems are designed to utilize the advantages of each energy source while addressing their weaknesses. The main goal of a hybrid system is to increase reliability and economic efficiency by integrating two or more energy sources. In the context of street lighting, this system typically consists of solar panels, wind turbines, energy storage batteries, charge controllers, and LED lights as the final load.

Solar panels (photovoltaic/PV cells) convert sunlight directly into electrical energy through the photovoltaic effect. Polycrystalline panels with a capacity of 50 watts (WP) were used in this study, with a conversion efficiency of around 13–16%. To maximize energy capture, the panels were mounted at a perpendicular angle to the sun's rays. On the other hand, the Savonius wind turbine is a type of vertical turbine suitable for low wind speeds, boasting self-starting capability, a symmetrical design, and stability in various wind directions without the need for a yaw mechanism. This turbine is coupled to a DC generator to convert the wind's kinetic energy into electrical energy. The energy generated by both sources is stored in a 12V 15Ah battery connected in parallel to increase storage capacity. The battery serves as a power source when the primary source is inactive and stores excess energy generated.

To regulate the charging process and prevent overcharging or deep discharge, a PWM (Pulse Width Modulation) Solar Charge Controller (SCC) is used, which is effective and economical for small-scale off-grid systems (Hadi et al., 2023). Additionally, a MIC 6A10 rectifier diode is installed to prevent backflow from the battery to the solar panel or generator when there is no energy production.

LED lights are used as the primary load due to their high efficiency, long lifespan, and low power consumption. Adequate lighting not only improves the safety and comfort of road users but also supports economic and social activities at night and reduces the potential for crime. Based on this background, this study aims to design, implement, and evaluate the performance of a hybrid solar and wind power generation system for public street lighting. This system is expected to be a sustainable, independent energy solution, reducing dependence on fossil fuels, and reducing operational costs and greenhouse gas emissions. This research makes several key contributions, namely:

- Design and implementation of a prototype-scale solar power plant system integrating solar panels and a Savonius wind turbine for public street lighting applications.
- Optimization of the combination of complementary renewable energy sources, thereby increasing the reliability of electricity supply during the day and night.
- Empirical evaluation of system performance, including energy conversion efficiency, battery storage capacity, and output voltage stability.
- The use of economical and readily available components allows the system to be replicated in remote or urban areas with limited budgets.
- Practical understanding of hybrid component integration, including the role of SCC PWM, safety diodes, and load management, which can be a reference for renewable energy researchers and practitioners.

2. METHOD

2.1. SAVONIUS TURBINE

The Savonius wind turbine is a type of vertical axis wind turbine (VAWT) invented by Finnish engineer Sigurd J. Savonius in 1923. It is designed to convert the kinetic energy of wind into mechanical (rotational) energy, which can then be used to drive an electrical generator. The Savonius turbine is known for its simple design, resembling an inverted "S" or two half-tubes facing each other, hence the name "bucket-type" rotor. The Savonius turbine operates based on drag, rather than lift like a horizontal turbine [8][9][10][11][12].

- Wind strikes the concave part of one of the "buckets" (blades).
- Due to its asymmetrical shape, the drag force on one side is greater than the other.
- This difference in force creates a torque (turning moment) that causes the rotor to rotate.
- The rotation of the vertical shaft is coupled to a DC generator to generate electricity.

Savonius Turbine Applications

- Hybrid Street Lighting (Solar + Wind)
- Agricultural Irrigation Systems
- Water Pumps in Remote Areas
- Charging Stations for Small-Scale Electric Vehicles
- Building Ventilation Systems

Savonius wind turbines are a practical and economical solution for harnessing wind energy in areas with low or unstable wind speeds. While their efficiency is not as high as that of horizontal turbines, their reliability, self-starting capability, and ease of maintenance make them well-suited for hybrid applications with solar panels, particularly in off-grid street lighting projects.

TABLE 1. ADVANTAGES OF SAVONIUS TURBINE

Savonius Turbine Advantages	Explanation
Self-Starting	It can start spinning even at low wind speeds (1–3 m/s).
No Yaw Mechanism Required	Because it has a vertical axis, this turbine can receive wind from any direction without having to rotate with it.
Simple and Robust Design	It is easy to construct from local materials (iron, plastic, used drums), and is resistant to extreme weather conditions.
Suitable for Urban Areas	It can be installed on rooftops because it is not too high and is quiet.
Low Maintenance Costs	It has few mechanical components, so it rarely breaks down.

Details of the advantages of the Savonius turbine can be seen in Table 1. These advantages make the Savonius turbine very popular for small and medium scale applications, especially in rural or urban areas. Simple Calculation of Generated Power. The basic formula for wind turbine power is:

$$P = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \cdot C_p \qquad (1)$$

Where P is power (W). ρ is Air density (~1.225 kg/m³). A is Rotor cross-sectional area (m²). v is Wind speed (m/s). C_p is Power coefficient (for Savonius, $C_p \approx 0.15-0.20$). Savonius wind turbines are a practical and economical solution for harnessing wind energy in areas with low or unstable wind speeds. While their efficiency is not as high as that of horizontal turbines, their reliability, self-starting capability, and ease of maintenance make them well-suited for hybrid applications with solar panels, particularly in off-grid street lighting projects.

2.2. SOLAR PANEL

A solar panel (or photovoltaic cell) is a semiconductor device that converts sunlight directly into electrical energy through the photovoltaic effect. These panels consist of many solar cells arranged in series and parallel to produce sufficient voltage and current for household, industrial, or infrastructure applications such as street lighting [13][14][15][16][17]. The energy conversion process in solar panels involves three main stages:

- Light Absorption : When photons (light particles) from sunlight strike a semiconductor layer (usually silicon), the photon's energy is absorbed by atoms in the material.
- Charge Separation : The photon's energy releases electrons from their atomic bonds, creating electron-hole pairs. A p-n junction layer (the junction of p-type and n-type semiconductors) creates an electric field that separates the electrons and holes, pushing electrons toward the n-layer and holes toward the p-layer.
- Electric Current Formation : This charge separation creates a potential difference (voltage). When connected to a load (such as a lamp or battery), electrons flow through an external circuit, producing direct current (DC).

TABLE 2. TYPES OF SOLAR PANELS

Types	Advantages	Disadvantages
Monocrystalline	- High efficiency (18–22%), Long lifespan, Limited space	- Higher cost, More wasteful silicon production
Polycrystalline	- More affordable, More energy-efficient production	- Lower efficiency (15–17%), Performance drops faster when hot
Thin-Film	- Flexible, lightweight, Good performance in low light	- Very low efficiency (10–13%), Requires a larger area

Each type of solar panel has different characteristics, so the choice depends on specific needs such as budget, available space, and environmental conditions. A detailed explanation can be found in Table 2. Factors Affecting Solar Panel Performance

- Sunlight Intensity (Irradiance) : The higher the light intensity, the greater the current generated.
- Mounting Angle and Orientation : Panels should be installed at an optimal angle (usually 15°–30° depending on latitude) and facing south (in the Southern Hemisphere) to capture maximum light.
- Ambient Temperature : Efficiency decreases as temperature increases. For every 1°C increase above 25°C (STC), efficiency drops by approximately 0.3–0.5%.
- Shadows and Dust: Shadows on one part of the panel can reduce overall output. Dust also reduces light transmission.
- Inverter and Charge Controller Quality: For off-grid systems, a charge controller (PWM/MPPT) is crucial for regulating battery charging and preventing overcharging.

Simple Calculation of Power Generated

$$P = G \ x \ A \ x \ \eta \qquad (2)$$

Where P is electrical power (Watts). G is sunlight intensity (~1000 W/m² at STC conditions). A is panel area (m²). η is panel efficiency (e.g., 15% = 0.15). Solar panels are a key technology in the renewable energy transition, particularly for off-grid applications such as street lighting. While their efficiency depends on environmental conditions, integration with batteries, charge controllers, and other energy sources (such as wind turbines) makes them a sustainable, cost-effective, and environmentally friendly solution for the future.

2.3. SOLAR CHARGE CONTROLLER (SCC)

A solar charge controller (or solar regulator) is an electronic device that regulates the flow of electricity from solar panels to storage batteries in off-grid or hybrid systems. Its primary function is to optimize the battery charging process while preventing damage from overcharging or over-discharging [18][19][20][21]. In a hybrid power generation system for public street lighting:

A solar charge controller (PWM) is used to regulate the charging from the solar panels.

- If the wind turbine also produces DC current, a dual-input controller or two separate controllers (one for solar, one for wind) can be used.
- The battery (12V 15Ah) is charged by both sources, and the controller ensures the battery does not overcharge.
- The LED lights are automatically turned on when dark, powered by the battery.

Advantages of Using a Solar Charge Controller

- Extends battery life by 2–3 times.
- Increases system efficiency by up to 30% (especially with MPPT).
- Prevents system failure due to overvoltage or deep discharge.
- Provides better control and monitoring.

A solar charge controller is a crucial component in any solar or hybrid power system. Without a controller, the system will be unstable and the battery will quickly deteriorate. For small-scale hybrid street lighting projects, a PWM controller is quite effective and economical. However, for large or professional systems, an MPPT is the best choice for maximum efficiency. Table 3 is the main function of the solar charge controller the solar charge controller is a critical component in a solar power system that functions as the "brain" to regulate and protect the entire system.

TABLE 3. MAIN FUNCTION OF SOLAR CHARGE CONTROLLER

Functions	Explanation
Prevent Overcharging	Stops charging when the battery is fully charged (100%) to prevent overheating and damage.
Prevent Deep Discharge	Cuts off power to the load when the battery voltage is too low (e.g., <11.5V for a 12V battery), preventing permanent damage.
Charging Optimization	Regulates the charging process according to the following stages: bulk, absorption, and float.
System Protection	Protects against reverse current, short circuits, and voltage surges.
Monitoring	Some models feature an LCD display or app connection to monitor voltage, current, and battery status.

2.4. DC GENERATOR

A DC (Direct Current Generator) generator is an electrical machine that converts mechanical energy (rotational motion) into direct current (DC) electrical energy. These generators are widely used in small-scale power generation systems, especially in applications that require direct DC voltage, such as battery charging in solar power systems, Savonius wind turbines, or hybrid power plants [22][23][24][25]. The general process is as follows:

- The rotor (armature) rotates within a magnetic field generated by the stator (magnetic poles).
- When the rotor coils cut the magnetic lines of force, an electrical voltage is induced.
- The AC voltage generated in the coils is converted to DC voltage by the commutator and carbon brushes.
- This DC voltage is then sent to the external circuit (battery, lamp, etc.).

Advantages of DC Generators

- Produces direct current (DC), suitable for battery charging.
- Stable voltage at a constant speed.
- Simple design and easy maintenance (especially PMDC).
- Can directly charge batteries without the need for an inverter.
- Efficient for off-grid and small-scale systems.

DC generators, particularly permanent magnet (PMDC) types, are key components in small-scale wind power generation systems and hybrid systems. Although they have some limitations, such as carbon brush wear, their reliability, ability to generate direct DC voltage, and compatibility with batteries make them an ideal choice for off-grid applications such as hybrid street lighting. With proper integration with wind turbines, charge controllers, and batteries, DC generators can make a significant contribution to the development of independent and sustainable renewable energy.

3. PROPOSED METHOD

The research employed an experimental method, which involves the manipulation and control of variables to determine their relationship and effect on the system. In this study on a hybrid power generation system for public street lighting, the experimental approach included the measurement and analysis of key environmental parameters such as wind speed, ambient temperature, solar irradiation, and lighting requirements. These data were used to design, simulate, and evaluate the performance of the hybrid power system. The system design began with the development of a detailed electrical schematic for the hybrid power plant, as illustrated in Figure 1 . The hybrid system integrates solar panels and a Savonius wind turbine to generate electricity. The solar panels convert sunlight into direct current (DC) electricity, while the wind turbine harnesses wind energy to rotate a generator, producing electrical power. To ensure system reliability, a 6A diode (MIC 6A10) is installed to prevent reverse current flow from the battery to the generator or solar panel when no power is being generated.

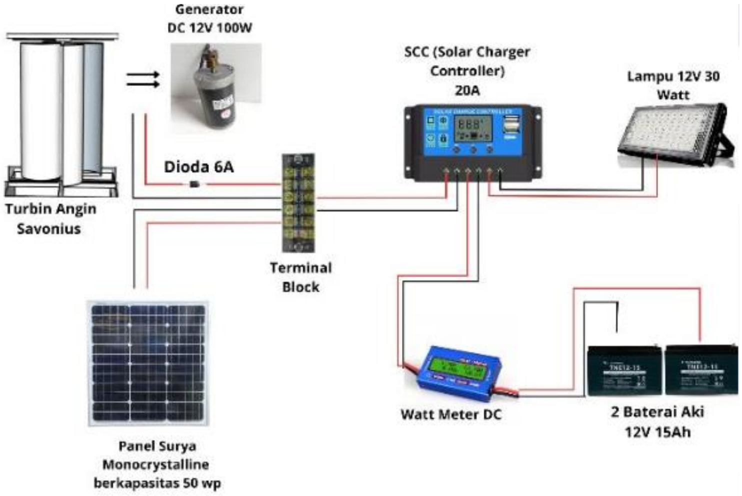

Figure. 1. Tool Design

A Pulse Width Modulation (PWM) Solar Charge Controller (SCC) regulates the charging process to prevent overcharging and deep discharging of the battery, thereby extending its lifespan. The generated electrical energy is stored in a 12V lead-acid battery, enabling continuous power supply during nighttime or periods of low sunlight and wind. This stored energy powers LED street lights, ensuring consistent, reliable, and energy-efficient illumination. Figure 2 presents the final configuration of the designed hybrid power system, demonstrating the integration of all components into a functional prototype.

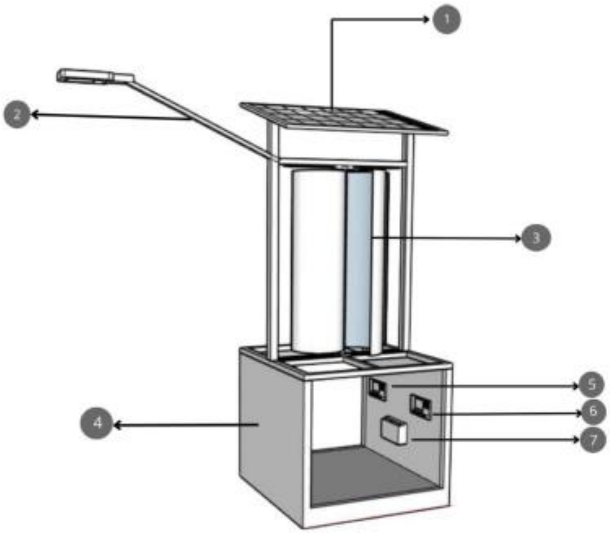

Figure. 2. Tool Design Results

Image Captions
1. 30W Solar Panel
2. 30W LED Light
3. Savonius Wind Turbine
4. Panel Box
5. Watt Meter
6. Solar Charge Controller
7. Battery

4. RESULT AND DISCUSSION

This hybrid power system integrates two renewable energy sources: solar and wind energy. Solar panels convert sunlight into direct current (DC) electricity through the photovoltaic effect, while a wind turbine drives a DC generator to convert kinetic wind energy into electrical power. The electricity generated from both sources is combined and regulated through a charge controller before being stored in a battery bank for later use. In this study, the stored energy is utilized to power 30-watt LED street lights, which operate on DC, ensuring efficient and reliable illumination for public lighting applications.

TABLE 4. SOLAR PANEL TESTING DAY 1

Time	No Load			Energy	Temperature
	V	A	W	Wh	
08:00	11.65	0.62	7.9	7.9	28
09:00	12.77	0.68	8.7	16.6	29
10:00	12.65	0.82	10.3	26.9	31
11:00	13.16	0.9	11.9	38.8	32
12:00	14.7	0.85	12.5	51.3	33
13:00	14.62	0.87	12.7	64	34
14:00	14.29	0.79	11.3	75.3	34
15:00	13.27	0.7	9.2	84.5	33
16:00	12.74	0.68	9	93.5	33
17:00	12.32	0.69	8.6	102.3	32

Table 4 shows that the highest voltage produced by the solar panel was 14.62 W at 1:00 PM, while the lowest voltage produced by the solar panel was 11.65 W at 8:00 AM. The energy produced on the first day of solar panel testing was 102.3 W.

TABLE 5. SOLAR PANEL TESTING DAY 2

Time	No Load			Energy	Temperature
	V	A	W	Wh	
08:00	11.2	0.5	5.6	5.6	28
09:00	12	0.6	7.2	12.8	28
10:00	12.7	0.7	8.8	21.6	30
11:00	12.72	0.79	10.1	31.7	32
12:00	13.02	0.84	10.9	42.6	33
13:00	13.14	0.87	11.4	54	34
14:00	12.96	0.67	8.6	62.6	33
15:00	12.47	0.62	7.7	70.3	31
16:00	11.64	0.61	7.1	77.4	31
17:00	10.86	0.56	6	83.4	30

Table 5 shows that the highest voltage produced by the solar panel was 13.14 W at 1:00 PM, while the lowest voltage produced by the solar panel was 10.85 W at 5:00 PM. The second day of testing was noticeably lower than the previous day due to the weather conditions and lower sunlight intensity on the second day. The energy produced on the second day of testing was certainly lower, at 83.4 W. The output measurement is a 12V 30Ah battery. The battery is powered by two power sources: a DC generator and a solar panel. This measurement produces a load current and a 12V voltage connected to a DC lamp load. To determine the usage time of the 12V 30Ah battery. The resulting voltage is 12V and the current is 2A for a 30W load. The calculated usage time for a 30W lamp load is 12 hours. The lamp will automatically turn on at night and turn off during the day because the lamp load is equipped with a solar charge controller that is set to run for 12 hours. The calculated usage time for a 30W lamp load is 15 hours. However, during field testing, the lamp can be set to run for 12 hours.

5. CONCLUSION

This study successfully designed and implemented a hybrid power generation system (PLTH) that integrates solar and wind energy for standalone public street lighting. The system offers a sustainable solution to reduce fossil fuel dependence and environmental impact, while enhancing the reliability of public infrastructure power supply. The hybrid system comprises a 50 WP solar panel, a Savonius wind turbine with a DC generator, a 12V 30Ah battery, a PWM solar charge controller, and a 30W LED lamp. These renewable sources complement each other: solar energy provides optimal power during daylight, while the wind turbine operates continuously, including at night or during cloudy weather, improving overall system stability and reliability. Solar panel testing over two days showed responsive performance to environmental conditions. On the first day, maximum power reached 12.7 W at 13:00, generating 102.3 Wh. On the second day, reduced sunlight due to overcast conditions lowered output to 83.4 Wh, with peak power of 11.4 W. This confirms the system's weather dependency, highlighting the importance of wind energy for continuous power supply. Generated energy is regulated by a PWM charge controller and stored in the battery, which powers a 30W LED lamp for 12 hours automatically at night. Although theoretical calculations suggest up to 15 hours of operation, field testing confirmed stable 12-hour performance, with automatic on/off control based on ambient light. The system maintains stable voltage (12V) and current (2A), ensuring consistent lighting without harmful fluctuations. The hybrid system proves capable of providing sufficient, efficient, and reliable electricity for street lighting. Its design makes it ideal for urban and remote areas without access to the PLN grid. This research contributes to the development of independent, environmentally friendly, and sustainable energy infrastructure. Future improvements could include IoT-based monitoring and component optimization to enhance efficiency and system lifespan.

REFERENCES

[1] S. Goel, S. Rathor, S. Sharma, and U. Sharma, “Harnessing Piezoelectric Energy for Smart Streetlights and Wastebin Automation,” in *2025 2nd International Conference on Computational Intelligence, Communication Technology and Networking (CICTN)*, IEEE, 2025, pp. 415–421. https://doi.org/10.1109/CICTN64563.2025.10932539

[2] S. Biswas and M. Sinha, “Dynamic Street Lighting based on Adaptive Learning,” in *2025 International Conference on Computer, Electrical & Communication Engineering (ICCECE)*, IEEE, 2025, pp. 1–8. https://doi.org/10.1109/-ICCECE61355.2025.10940489

[3] P. K. Malik, A. Kumar, G. Sethi, S. Thapliyal, S. Aluvala, and S. Khera, “IoT-Enabled Smart Unidirectional Road Lighting Control System for Enhanced Energy Efficiency and Road Safety Through Sensor Integration and Geofencing Technology,” in *2025 3rd International Conference on Disruptive Technologies (ICDT)*, IEEE, 2025, pp. 436–441. https://doi.org/10.1109/ICDT63985.2025.10986328

[4] F. Wu, Y. Zhou, and Y. Luo, “Intelligent Control System for Campus Street Lighting Based on Microcontroller,” in *2025 7th International Conference on Information Science, Electrical and Automation Engineering (ISEAE)*, IEEE, 2025, pp. 419–423. https://doi.org/10.1109/ISEAE64934.2025.11042012

[5] S. S. Saranya and M. S. S. A. Tammana, “Integrating LoRa Technology for Smart Streetlight Systems: Enhancing Fault Detection and Adaptive Illumination,” in *2025 2nd International Conference on Research Methodologies in Knowledge Management, Artificial Intelligence and Telecommunication Engineering (RMKMATE)*, IEEE, 2025, pp. 1–7. https://doi.org/10.1109/RMKMATE64874.2025.11042823

[6] W. A. Jabbar, T. K. Keat, F. A. Dael, L. C. Hong, Y. F. M. Yussof, and A. Nasir, “Optimising urban lighting efficiency with IoT and LoRaWAN integration in smart street lighting systems,” *Discov. Internet Things*, vol. 5, no. 1, 2025, doi: https://doi.org/10.1007/s43926-025-00163-z

[7] M. Lima, S. Perinhas, J. Sousa, C. Viveiros, and F. Barata, “Integration of Solar PV and Battery Energy Storage Systems Towards a Sustainable Street Lighting,” in *2025 21st International Conference on the European Energy Market (EEM)*, IEEE, 2025, pp. 1–6. https://doi.org/10.1109/EEM64765.2025.11050106

[8] C. N. Savithri and V. Varun, “Dual-Turbine Hybrid Energy System for Fishing Boats,” in *2025 International Conference on Computing and Communication Technologies (ICCCT)*, IEEE, 2025, pp. 1–4. https://doi.org/10.1109/ICCCT63501.2025.11018982

[9] N. A. Mwero, P. Garcia–Novo, D. Sakaguchi, R. Yamada, and Y. Kyozuka, “Optimized Design Search of Tidal Turbine with Low Cut-in Speed for Energy Harvesting Smart Buoys,” in *2024 13th International Conference on Renewable Energy Research and Applications (ICRERA)*, IEEE, 2024, pp. 1537–1546. https://doi.org/10.1109/ICRERA62673.2024.10815285

[10] N. Rabeh, A. Ayadi, and Z. Driss, “Improving the Performance of a Savonius Rotor Through Blade Shape Modification,” in *2024 IEEE International Multi-Conference on Smart Systems & Green Process (IMC-SSGP)*, IEEE, 2024, pp. 1–4. https://doi.org/10.1109/IMC-SSGP63352.2024.10919743

[11] G.-A. Mătuşa, M.-C. Mareş, and P. Svasta, "Development of an Electronic Monitoring System for a Savonius Wind Turbine," in *2024 IEEE 30th International Symposium for Design and Technology in Electronic Packaging (SIITME)*, IEEE, 2024, pp. 222–226. https://doi.org/10.1109/SIITME63973.2024.10814894

[12] C. N. Savithri and V. Varun, "Integrating Wind Energy Systems In Fishing Boats," in *2024 International Conference on Power, Energy, Control and Transmission Systems (ICPECTS)*, IEEE, 2024, pp. 1–3. https://doi.org/10.1109/ICPECTS62210.2024.10780075

[13] L. Bruno and V. G. Monopoli, "An Innovative Strategy for Common-Mode Voltage Reduction in Three-Phase Voltage-Source Inverters Based on Pulse Position Modulation," *IEEE Trans. Ind. Electron.*, 2025.

[14] L. R. Yeddula, A. Pallakonda, R. D. A. Raj, R. M. R. Yanamala, K. K. Prakasha, and M. S. Kumar, "YOLOv8n-GBE: A Hybrid YOLOv8n Model with Ghost Convolutions and BiFPN-ECA Attention for Solar PV Defect Localization," *IEEE Access*, 2025. https://doi.org/10.1109/ACCESS.2025.3584249

[15] Y. Yang, B. Li, Z. Rong, S. Qu, and X. Cheng, "Spatio-temporal Analysis of Dust Devils in the Preselected Landing Area for Tianwen-3: A Case Study of Chryse Planitia," *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.*, 2025. https://doi.org/10.1109/JSTARS.2025.3581445

[16] M. Wahbah, S. Elshehaby, and A. Naimi, "Optimizing Solar Irradiance Estimation for Smart Green Cities using an Error-tuned Hybrid Beta-KDE Approach," in *IEEE EUROCON 2025-21st International Conference on Smart Technologies*, IEEE, 2025, pp. 1–5. https://doi.org/10.1109/EUROCON64445.2025.11073338

[17] R. Satheesh and A. Mohan, "Sustainable Irrigation System Using Solar Panel Tracking and IoT Integration," in *2025 3rd International Conference on Inventive Computing and Informatics (ICICI)*, IEEE, 2025, pp. 1694–1699. https://doi.org/10.1109/ICICI65870.2025.11069585

[18] A. Z. Arsad, A. W. M. Zuhdi, A. D. Azhar, C. F. Chau, and A. Ghazali, "Advancements in maximum power point tracking for solar charge controllers," *Renew. Sustain. Energy Rev.*, vol. 210, p. 115208, 2025. https://doi.org/10.1016/j.rser.2024.115208

[19] A. Z. Kouache, A. Djafour, K. M. S. Benzaoui, A. Gougui, M. B. Danoune, and M. Ramdani, "Field investigation of green hydrogen production via indirect coupling of PEM electrolyzer in southeast Algeria," *Int. J. Hydrogen Energy*, 2024. https://doi.org/10.1016/j.ijhydene.2024.10.025

[20] M. Naik, A. P. Singh, N. R. Pradhan, A. M. Almuhaideb, and N. Kumar, "A Framework for Blockchain-Enabled Internet of Electric Vehicle Charging Station Sustainability Performance Evaluation," *IEEE Internet Things J.*, 2024. https://doi.org/10.1038/s41598-025-00501-9

[21] L. P. R. Nadimuthu, K. Victor, M. Bajaj, V. Blazek, and L. Prokop, "Solar-thermoelectric mobile storage system integrated with electric vehicles for reducing postharvest and microbial losses in agro produce transportation," *Sci. Rep.*, vol. 15, no. 1, p. 15522, 2025. https://doi.org/10.1038/s41598-025-00501-9

[22] Y. Xu and Z. Zhang, "Generator Rectification in More Electric Aircraft High-voltage DC Electric Power Systems: A Review," *IEEE Trans. Transp. Electrif.*, 2025. https://doi.org/10.1109/TTE.2025.3557420

[23] D. Chakroborty, S. Singha, B. Mondal, A. Lata, and R. Sarkar, "Design and Development of IoT-Based Wireless Volumetric Flow Transmitter With Hemispheric Type Cup System," *IEEE Trans. Instrum. Meas.*, 2025. https://doi.org/10.1109/TIM.2025.3550212

[24] I. A. Reyes-Portillo, A. Claudio-Sánchez, S. R. M. Elizondo, D. L. Castro-López, and L. G. Carreto-Hernández, "Analysis of Kinetic Energy Recovery System Based on Four-Phase Interleaved Buck Converter for Vehicle Verification Processes," *IEEE Lat. Am. Trans.*, vol. 23, no. 6, pp. 527–536, 2025. https://doi.org/10.1109/TLA.2025.11007189

[25] W. Liu, Y. Tao, and X. Meng, "The Voltage Control Strategy for Doubly Salient Electromagnetic Generator with Active Rectifier Based on Optimal Current Distribution," *IEEE Access*, 2025. https://doi.org/10.1109/ACCESS.2025.3561782