IKR Publishers

IKR Journal of Engineering and Technology (IKRJET)

Journal homepage: ***https://ikrpublishers.com/ikrjet/***

Volume-1, Issue-1 (July-August) 2025

ISSN: 3107-7331 (Online)

The Assessment of the Efficacy of a Locally Designed and Implemented Solar-Powered Refrigerator System

[1]Jimoh A. A.*, [2]Abdulkadir Z. A., [3]Mukthar A.,[4]Mumin A. [5]Bello B. A., [6]Abdullahi K. A., and [7]Ambali O. A.

[1,2,3,4,5,6,7] Department of Electrical & Electronic Engineering, Institute of Technology, Kwara State Polytechnic, Ilorin

**Corresponding author: Akanbi Jimoh*

ARTICLE INFO

Article history:

Received : 28-06-2025

Accepted : 01-07-2025

Available online : 04-07-2025

Keywords: *Solar-Powered Refrigeration, Electrical Efficiency, Renewable Energy, Locally Design System and Freezing Rate.*

ABSTRACT ***Original research paper***

This study evaluates the electrical design efficiency of a local design and implementation solar-powered refrigerator system aimed at addressing refrigeration challenges in off-grid and underserved regions. The system utilizes locally available materials to ensure sustainability, affordability, and ease of maintenance. Key electrical parameters such as voltage, current, power consumption, and efficiency metrics were analyzed to optimize energy utilization and system performance. Normality tests confirmed the reliability of freezing time data collected at five-minute intervals. Comparative analysis of single-battery and dual-battery configurations demonstrated the impact of energy storage capacity on cooling performance. The findings highlight the potential of locally designed solar refrigeration systems to provide energy-efficient, cost-effective, and environmentally sustainable cold storage solutions, contributing to improved food security and healthcare storage in areas with unstable electricity supply. Recommendations for further optimization include advanced energy management strategies and integration of smart control mechanisms to enhance system reliability and longevity.

1. Introduction

The ability to store perishable goods efficiently is essential for food security, healthcare, and economic activities, particularly in regions with unstable electricity supply. However, inconsistent access to reliable power sources poses significant challenges, leading to food spoilage, inadequate medical storage, and economic losses for businesses reliant on refrigeration (Righetto *et al.,* 2021). While conventional refrigeration systems offer a solution, their dependence on grid electricity and high operational costs make them impractical in off-grid or underserved areas. As a result, solar-powered refrigeration systems have emerged as a sustainable alternative, providing an energy-efficient and environmentally friendly solution for regions facing electricity instability. The energy efficiency of solar-powered refrigeration systems is crucial for ensuring optimal performance, reliability, and cost-effectiveness (Christopher *et al.*, 2021). Since these systems depend entirely on solar energy, minimizing energy losses and optimizing power consumption is essential to sustain continuous operation, reduce battery dependency, and maximize system lifespan. Efficient electrical design, including effective solar power utilization, proper battery sizing, and minimal energy wastage, plays a key role in determining the system's overall efficiency and long-term sustainability (Muhammad and Asif, 2023).

In regions where imported refrigeration systems are expensive or impractical, the development and evaluation of locally fabricated solar-powered freezer systems provide an alternative solution. Locally designed systems can be tailored to specific environmental conditions, economic constraints, and available resources, making them a viable option for households, small businesses, and medical facilities (Jimoh *et al.,* 2017). Assessing the electrical design efficiency of these systems is critical in determining their cooling performance, energy consumption, durability, and compatibility with renewable energy sources (Arafat *et al.,* 2024). The need for evaluating the electrical design efficiency of solar-powered freezers arises from challenges such as unstable electricity supply, high energy costs, inefficient refrigeration technologies, and the lack of affordable cold storage solutions (Salcedo *et al.,* 2018). Analyzing and optimizing the electrical design, it is possible to enhance energy efficiency, improve system performance, and ensure cost-effective operation. Expanding research on electrically optimized solar-powered freezer systems can significantly contribute to better food preservation, improved healthcare storage, and increased economic resilience in off-grid and underserved areas (Chang and Wu, 2011). Despite its benefits, developing an electrically efficient solar-powered freezer system presents several technical challenges. Key issues include intermittent solar energy availability, high initial setup costs, and the need for advanced energy management strategies to ensure consistent and efficient operation. Factors such as solar panel efficiency, charge controller effectiveness, battery capacity, and thermal insulation play a crucial role in maintaining optimal refrigeration performance. Additionally, overcoming power losses, improving energy storage systems, and integrating smart control mechanisms are necessary to maximize electrical efficiency (García *et al.*, 2020).

To achieve a highly efficient solar-powered freezer system, careful design optimization, integration of advanced power management techniques, and the use of high-efficiency refrigeration components are required. Addressing these challenges through innovative electrical design, improved component selection, and optimized system configurations will enhance the reliability, affordability, and accessibility of solar-powered refrigeration solutions. This study aims to evaluate the electrical design efficiency of a locally fabricated solar-powered freezer system, identifying key performance indicators and recommending improvements for energy optimization and long-term sustainability. The other sections of this article are as follows: Section 2 presents the evolution of electrical design efficiency in solar-powered refrigerator systems, Section 3 highlights the materials and methods, Section 4 presents the results and discussion, while Section 5 concludes and gives recommendations for further areas of research.

2. Evolution of Electrical Design Efficiency in Solar-Powered Refrigerator Systems

The development of solar-powered refrigeration systems has evolved alongside advancements in photovoltaic (PV) technology, energy storage solutions, and thermal management techniques (Christopher *et al.*, 2021). Between the 1950s and 1980s, early solar refrigeration systems primarily relied on absorption cooling, with manually optimized system configurations due to limited computational tools and inefficiencies in photovoltaic conversion (Christopher *et al.*, 2023). The design approach was largely empirical, with system parameters such as solar panel capacity and battery storage determined through trial and error. The 1990s marked a shift towards improved solar-powered refrigeration, driven by enhancements in semiconductor technology and battery storage (Hu and Yue, 2021). The introduction of deep-cycle lead-acid batteries enabled more reliable energy storage, while advancements in maximum power point tracking (MPPT) improved solar energy utilization. However, system efficiency remained constrained by high thermal losses and limited compressor performance. Early direct current (DC) compressor designs required manual tuning of operational parameters such as voltage regulation and duty cycle to optimize performance (Ardila-Rey *et al.*, 2020).

In the early 2000s, electronic control systems and improved battery technologies, such as lithium-ion batteries, enhanced the feasibility of solar-powered freezers (Dhindsa, 2021). The integration of MPPT controllers and pulse-width modulation (PWM) techniques allowed for more precise energy management. Research on thermoelectric cooling and phase change materials (PCM) provided alternative methods to enhance thermal storage and improve cooling efficiency. Studies focused on optimizing compressor cycling, thermal insulation, and refrigerant selection to minimize energy losses (Salilih and Birhane, 2019).

Between 2015 and 2020, significant advancements in power electronics and system automation led to the adoption of smart control strategies in solar refrigeration (Adebayo *et al.*, 2024). Internet of Things (IoT)-based monitoring systems enabled real-time data acquisition and adaptive control mechanisms, optimizing compressor speed and fan operation based on cooling demand. The transition from traditional vapor compression refrigeration to hybrid absorption-compression systems further enhanced energy efficiency. The use of variable frequency drives (VFD) allowed for dynamic control of compressor operation, reducing power consumption during off-peak cooling cycles (Obaideen *et al.*, 2022).

Recent developments leverage artificial intelligence (AI) and machine learning (ML) for predictive maintenance and optimization of solar-powered refrigeration systems (Badillo *et al.*, 2020). AI-driven models analyze historical performance data to optimize charge controllers, battery management, and compressor cycling patterns. Adaptive energy management systems now incorporate reinforcement learning-based optimization to enhance energy efficiency, minimize battery degradation, and improve overall system longevity. The integration of nanomaterials in thermal insulation and phase change materials has further reduced heat infiltration, improving cooling retention (Hu and Yue, 2021).

However, a significant research gap remains in assessing the electrical design efficiency of locally fabricated solar-powered freezer systems. While existing studies have explored general efficiency improvements, limited research has examined the impact of locally sourced components, indigenous fabrication techniques, and real-world performance variations. This study aims to bridge this gap by systematically analyzing the electrical design efficiency of a locally constructed solar-powered freezer system. Key contributions of this study:

- Evaluation of electrical efficiency parameters, including solar panel capacity, battery performance, charge controller optimization, and compressor power consumption in locally fabricated systems.

- Optimization strategies for improved efficiency, focusing on adaptive control techniques, energy storage management, and thermal load balancing.

Benchmarking performance of the locally fabricated system against conventional solar-powered refrigeration models to establish empirical insights into design efficiency.

3. Materials and Methods

The material and method employed for the project are in the local market to ensure sustainability, availability, and maintenance of the design. This allows for customization and design specifications as suitable for the type of storage required.

Table 1: The Local Refrigerator System Descriptions

Features Descriptions				
S/N	Materials/Components	Quantity	Functions	Rating
1	Solar Panel (Photovoltaic Cell)	3	converts sunlight into electrical energy	300 watts
2	Charge Controller	1	Control the voltage and current coming from the solar panels to the battery for effective charging	40 Amps MPPT
3	Battery	2	Serve as the storage mechanism for the energy generated by solar panels	100 AH
4	DC Compressor	1	Responsible for compressing refrigerant gas and circulating it through the cooling system.	250 watts, (12 – 24) Volts
5	Polyurethane Foam (Interior Lining)	-	Used for the cooling chamber and allow the process of cooling	-
6	Coated Steel (Exterior Cover)	-	To prevent corrosion of the outside cover	-

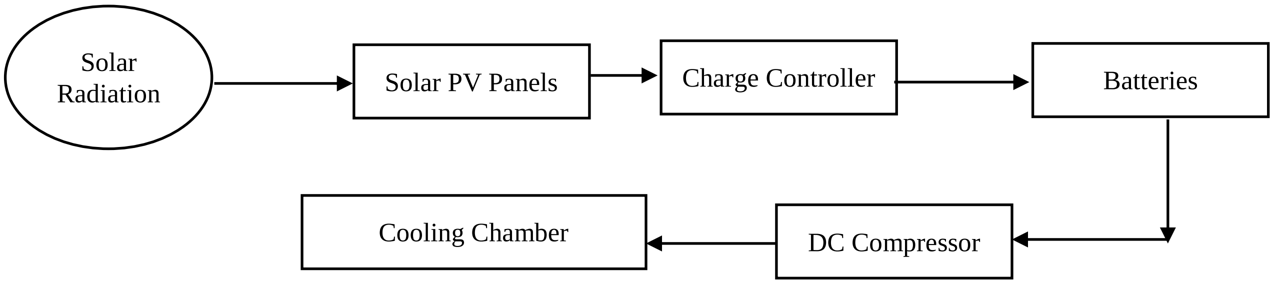


Figure 1: The Block Diagram of a Locally Design and Implemented Solar-Powered Refrigerator System

3.2 System Design and Implementation Considerations

The efficiency of a solar-powered Refrigerator system depends on various electrical parameters, including voltage, current, power consumption, and efficiency metrics. Understanding these parameters helps in optimizing energy utilization and improving overall system performance.

Figure 2: The depiction of the Solar-Powered Refrigerator Implementation System.

This section provides an in-depth explanation of these parameters and outlines the energy flow from solar panels to storage and refrigerator operation as depicted in the implementation diagram of Figure 2.

3.2.1 Voltage (V)

Voltage represents the electrical potential difference that drives current through the system. In a solar-powered fridge, voltage levels are determined by the photovoltaic (PV) array, battery bank, and the system's electrical components, like:

i. Solar panel output voltage: Typically ranges from 12V to 48V, depending on the system design. Higher-voltage panels reduce resistive losses and improve power transmission efficiency.
ii. Battery voltage: Lead-acid batteries typically operate at 12V or 24V, while lithium-ion batteries can function at higher voltages (48V or more) for increased efficiency.
iii. Compressor operating voltage: DC compressors generally require 12V, 24V, or 48V, depending on the design. An inverter is needed if an AC compressor is used (Jimoh *et al.*, 2017).

3.2.2 Current (I)

Current (measured in Amperes, A) determines the rate at which electric charge flows through the system. It is influenced by the load demand and system voltage.

i. Solar panel current output: Defined by the panel's power rating and operating voltage (e.g., a 100W panel at 12V produces approximately 8.3A under optimal conditions).
ii. Battery charging and discharging current: The charge controller regulates current flow to the battery to prevent overcharging or deep discharge. Deep-cycle batteries typically have a charge/discharge current range based on their amp-hour (Ah) capacity.
iii. Compressor current draw: A DC compressor draws about 3 Amps – 10 Amps, depending on cooling demand and system voltage.

3.2.3 Power Consumption (P)

Power (measured in Watts, W) is the product of voltage and current (P = V × I) and determines the energy demand of the system.

i. Solar panel power generation: The total power output depends on solar irradiance and panel efficiency (e.g., a 200W panel produces 200W under peak sunlight).
ii. Battery power supply: The energy stored in the battery must match the refrigerator's operational demand. A 100 AH, 12 V battery stores 1.2 kWh of energy.
iii. Compressor power demand: Typically ranges from 50 W to 150 W, depending on the cooling load, compressor type, and ambient temperature.

3.2.4 Efficiency Metrics

Efficiency metrics help evaluate the system's performance in converting and utilizing energy. Key metrics include:

i. Solar panel efficiency: Defined as the ratio of electrical energy output to solar energy input. Modern panels have efficiencies of 15% – 22%.
ii. Charge controller efficiency: Controllers optimize power transfer, with controller of high efficiency allow an optimal performance for the refrigerators over a low-efficiency charge controller.
iii. Battery round-trip: Lithium-ion batteries have a higher Depth of Discharge (DoD) than lead-acid batteries.
iv. Compressor efficiency (COP - Coefficient of Performance): Measures cooling output per unit power consumed. A COP of 1.5 – 3 is common for DC refrigeration systems .

3.2.5 Energy Flow in a Solar-Powered Refrigerator System

The energy flow in a solar-powered refrigerator system follows a structured pathway from solar energy harvesting to refrigeration operation.

i. Solar energy harvesting (Photovoltaic Panels), solar panels convert sunlight into DC electricity, generating voltage and current based on irradiation levels. The generated power is regulated by an MPPT or PWM charge controller, optimizing power flow to the battery and load.
ii. Energy Storage (Battery Bank), excess solar energy charges the battery bank for later use. The charge controller prevents overcharging and ensures controlled discharge. During low sunlight or nighttime, stored energy supplies the refrigerator.
iii. Power Regulation and Distribution, a DC-DC converter may adjust voltage levels to match compressor requirements. If an AC compressor is used, an inverter converts DC power to AC, with conversion losses (~5%–10%).
iv. Freezer Operation (Compressor and Thermal Management), the DC compressor cycles based on the temperature sensor and thermostat settings. Adaptive control techniques adjust compressor speed to reduce energy consumption. Insulation and phase change materials help retain cooling, minimizing power demand.
v. Performance Monitoring and Optimization, IoT-based controllers collect real-time data on voltage, current, temperature, and efficiency (Salilih and Birhane, 2019).

4. Results and Discussions

The Kolmogorov-Smirnov and Shapiro-Wilk tests were conducted to assess whether the data followed a Gaussian (normal) distribution and were not skewed (Landtblom, 2023). These normality tests were applied to the time intervals of data recording for the solar power supplies, as well as the corresponding freezing temperature values. Based on empirical observations, temperature measurements inside the refrigerator were recorded at 5-minute intervals, as significant changes were consistently detected at this frequency. This interval was determined to be optimal after several trial observations showed meaningful temperature variation every five minutes. All collected data were then entered into SPSS software to perform the normality tests and verify that the distribution of values met the assumptions for further statistical analysis.

Table 2: Normality Tests for the Freezing Time with One Battery

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	Df	Sig.	Statistic	Df	Sig.
Freezing _Time	.073	25	.200*	.959	25	.387

*. This is a lower bound of true significance.

a. Lilliefors Significance Correction

Given the Normality Test of Table 2, the results show that Kolmogorov-Smirnov Test has a significant value of 0.200 and the Shapiro-Wilk test shows a significant value of 0.387. The two significant values are well greater than 0.05 and therefore the freezing time is normal or has passed the normality test. The diagram in Figure 3 also depicts the Q-Q plot chart which provides a visual representation of the distribution of freezing time data. The chart shows that the freezing time data is normal and has the data forms a cluster of dots around or along the trend line. This further provides evidence that the freezing time data is normal.

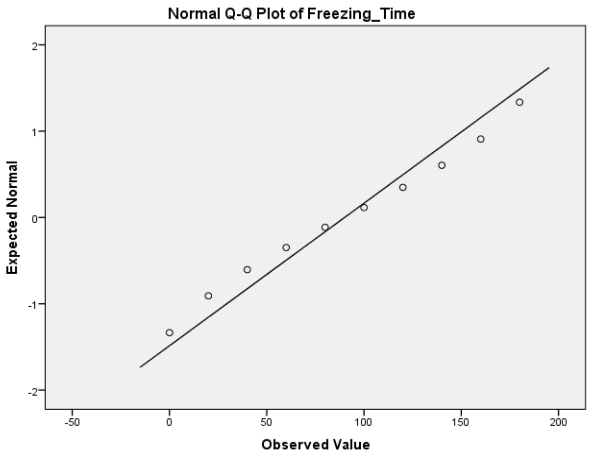
Table 3 Normality Tests for the Freezing Time with Two Battery

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	Df	Sig.	Statistic	Df	Sig.
Freezing_Time	.096	10	.200*	.970	10	.892

*. This is a lower bound of true significance.

a. Lilliefors Significance Correction

The result in the table shows that the significant values of 0.2 and 0.8 are far greater than 0.05 for Kolmogorov Smirnov and Shapiro Wilk respectively. These shows are normally distributed as shown in the Q-Q plot.



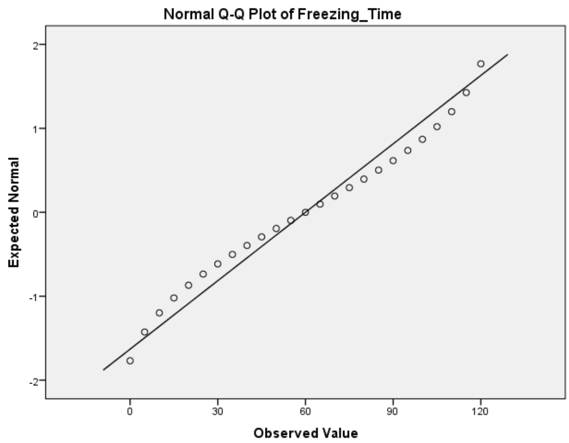


Figure 3: Q-Q plot depiction for Freezing Time with (a) One Battery and (b) Two Batteries

The freezing time performance of the implemented refrigerator system was analyzed using graphical comparisons for both single-battery and dual-battery configurations, as shown in Figure 4. The results revealed that with a single battery, the cooling rate of the system was relatively weak, indicating limited compressor efficiency. This was primarily attributed to insufficient current and voltage being supplied to the DC compressor, which restricted its compression capacity and, consequently, the overall cooling performance. In contrast, when the system was powered by two batteries, a noticeable improvement in cooling efficiency was observed. The increased voltage and current availability enhanced the compressor's operation, leading to a faster and more effective reduction in temperature over the same measurement time interval. This comparison highlights the significant role of adequate power supply in optimizing the performance of solar-powered refrigeration systems, particularly in ensuring effective temperature regulation and energy-efficient operation under varying load conditions.

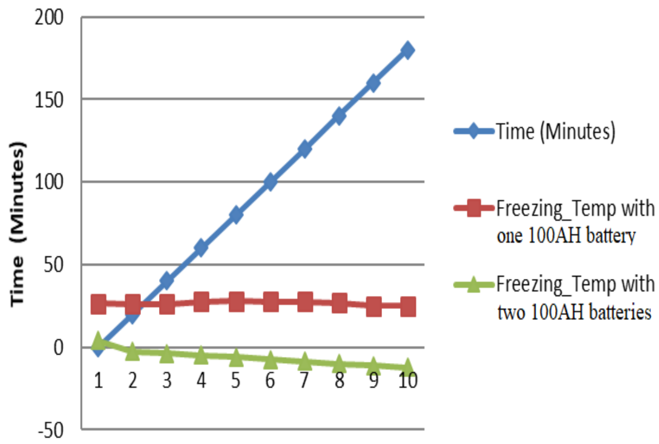


Figure 4: Freezing rate Graphical Comparison for the Refrigerator's Implementation System

5. Conclusions and Recommendations

The evaluation of the locally designed and implemented solar-powered refrigerator system confirms that electrical design efficiency is a critical factor influencing cooling performance and energy consumption. The system's reliance on solar energy necessitates careful optimization of components such as solar panels, batteries, charge controllers, and compressors to minimize energy losses and maximize operational sustainability. The study's normality tests validate the freezing time data, supporting the robustness of the performance analysis. Results indicate that increasing battery capacity significantly improves cooling rates, underscoring the importance of adequate energy storage in solar refrigeration applications. Locally sourced materials and design customization offer practical advantages for deployment in resource-constrained environments. Future work should focus on incorporating adaptive control techniques, enhanced thermal insulation, and IoT-based monitoring to further improve energy efficiency and system resilience. Conclusively, the research demonstrates that locally designed solar-powered refrigeration systems can play a vital role in enhancing food preservation, healthcare storage, and economic stability in off-grid communities.

References

1. Arafat, M. Y., Hossain, M. J., and Alam, M. M. (2024). Machine learning scopes on microgrid predictive maintenance: Potential frameworks, challenges, and prospects. *Renewable and Sustainable Energy Reviews*, *190*, 114088. https://doi.org/10.1016/j.rser.2023.114088
2. Ardila-Rey, J. A., Cerda-Luna, M. P., Rozas-Valderrama, R. A., De Castro, B. A., Andreoli, A. L., and Muhammad-Sukki, F. (2020). Separation Techniques of Partial Discharges and Electrical Noise Sources: A Review of Recent Progress. *IEEE Access*, *8*, 199449–199461. https://doi.org/10.1109/ACCESS.2020.3035249
3. Badillo, S., Banfai, B., Birzele, F., Davydov, I. I., Hutchinson, L., Kam-Thong, T., Siebourg-Polster, J., Steiert, B., and Zhang, J. D. (2020). An Introduction to Machine Learning. *Clinical Pharmacology & Therapeutics*, *107*(4), 871–885. https://doi.org/10.1002/cpt.1796
4. Chang, L., and Wu, Z. (2011). Performance and reliability of electrical power grids under cascading failures. *International Journal of Electrical Power & Energy Systems*, *33*(8), 1410–1419. https://doi.org/10.1016/j.ijepes.2011.06.021
5. Christopher, S. S., Santosh, R., Ponrajan Vikram, M., Prabakaran, R., Thakur, A. K., and Xu, H. (2021). Optimization of a solar water heating system for vapor absorption refrigeration system. *Environmental Progress and Sustainable Energy*, *40*(1), e13489. https://doi.org/10.1002/ep.13489
6. Christopher, S. S., Thakur, A. K., Hazra, S. K., Sharshir, S. W., Pandey, A. K., Rahman, S., Singh, P., Sunder, L. S., Raj, A. K., Dhivagar, R., and Sathyamurthy, R. (2023). Performance evaluation of external compound parabolic concentrator integrated with thermal storage tank for domestic solar refrigeration system. *Environmental Science and Pollution Research*, *30*(22), 62137–62150. https://doi.org/10.1007/s11356-023-26399-2
7. Dhindsa, G. S. (2021). Review on performance enhancement of solar absorption refrigeration system using various designs and phase change materials. *Materials Today: Proceedings*, *37*, 3332–3337. https://doi.org/10.1016/j.matpr.2020.09.125
8. García, L., Parra, L., Jimenez, J. M., Lloret, J., and Lorenz, P. (2020). IoT-Based Smart Irrigation Systems: An Overview on the Recent Trends on Sensors and IoT Systems for Irrigation in Precision Agriculture. *Sensors*, *20*(4), 1042. https://doi.org/10.3390/s20041042
9. Hu, T., and Yue, Z. (2021). Potential applications of solar refrigeration systems for permafrost cooling in embankment engineering. *Case Studies in Thermal Engineering*, *26*, 101086. https://doi.org/10.1016/j.csite.2021.101086
10. Jimoh A. A., Lawal O. A, and Kabiru L. (2017). Performance Equation Modeling for A 2 kVA Locally Designed and Constructed Inverter Systems. *International Conference of Science, Engineering & Environmental Technology*, *2*(4), 23–28.
11. Landtblom, K. (2023). Opportunities to Learn Mean, Median, and Mode Afforded by Textbook tasks. *Statistics Education Research Journal*, *22*(3), 6. https://doi.org/10.52041/serj.v22i3.655
12. Muhammad Asif. (2023). *Predictive Maintenance of Power Substation Equipment by Infrared Thermography* [Dataset]. Mendeley. https://doi.org/10.17632/XWYCX35GRK.1
13. Obaideen, K., Yousef, B. A. A., AlMallahi, M. N., Tan, Y. C., Mahmoud, M., Jaber, H., and Ramadan, M. (2022). An overview of smart irrigation systems using IoT. *Energy Nexus*, *7*, 100124. https://doi.org/10.1016/j.nexus.2022.100124

14. Righetto, S. B., Izumida Martins, M. A., Carvalho, E. G., Hattori, L. T., and De Francisci, S. (2021). Predictive Maintenance 4.0 Applied in Electrical Power Systems. *2021 IEEE Power and Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, 1–5. https://doi.org/10.1109/ISGT49243.2021.9372230
15. Salcedo-Sanz, S., Cornejo-Bueno, L., Prieto, L., Paredes, D., and García-Herrera, R. (2018). Feature selection in machine learning prediction systems for renewable energy applications. *Renewable and Sustainable Energy Reviews*, *90*, 728–741. https://doi.org/10.1016/j.rser.2018.04.008
16. Salilih, E. M., and Birhane, Y. T. (2019). Modelling and performance analysis of directly coupled vapor compression solar refrigeration system. *Solar Energy*, *190*, 228–238. https://doi.org/10.1016/j.solener.2019.08.017