

REVIEW ARTICLE

RETROFITTING AC REFRIGERATORS WITH DC COMPRESSORS: A COST-EFFECTIVE SOLAR-POWERED SOLUTION FOR OFF-GRID COMMUNITIES

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ARTICLE DETAILS

Article History:

Received 23 September 2025
Revised 15 October 2025
Accepted 21 November 2025
Available online 31 December 2025

ABSTRACT

A reliable cooling solution is critically needed but often unavailable in off-grid areas of sub-Saharan Africa, where persistent energy shortages and unstable power supply create a major obstacle for food preservation and storing vaccines. This study demonstrates a practical method for addressing this problem by retrofitting a standard AC refrigerator to run on solar-power using a Variable Speed Direct Current (VSDC) compressor. A 112L Haier Thermocool refrigerator was retrofitted with a ZH15G DC compressor, powered by a 300W monocrystalline solar panel, a 20A MPPT controller, and a 12V, 75Ah battery. The DC system cooled from 25°C to -3.2°C in 9 minutes, consuming 180 Wh/day—91.88% less than the AC system's 2,217.6 Wh/day. The conversion cost (₦310,000) was 36.7% lower than a new DC refrigerator (₦489,993), with a payback period of 3.55 years and an annual CO₂ reduction of 297.49 kg. Validated by a lumped capacitance thermal model, this scalable, cost-effective solution supports Sustainable Development Goals (SDGs) 7 and 13, addressing energy poverty in off-grid communities.

KEYWORDS

Solar refrigeration, DC compressor, VSDC compressor, energy efficiency, off-grid, thermodynamic modeling, sustainability

1. INTRODUCTION

More than 85 million people in Nigeria face power scarcity, which severely limits the ability to store vaccines and preserve food (World Bank, 2021). With the national grid experiencing frequent total failures—documented 12 times in 2024 alone—rural communities are left without dependable cooling (Punch, 2024). While Nigeria possesses significant solar potential (4.0–5.5 kWh/m²/day), adopting solar refrigeration is hindered by the high cost of specialized DC units and the 5–15% efficiency loss inherent in inverter-based AC systems (Oniyeburutan et al., 2020; Linqip, 2023).

Utilizing Variable Speed Direct Current (VSDC) compressors offers a solution by removing the need for inverters and allowing for dynamic cooling adjustments based on demand (Ekren et al., 2013). This technological approach is a cornerstone of distributed energy generation, which is essential for global sustainable growth (Alanne and Saari, 2006). By retrofitting existing AC cabinets with DC components, we can utilize current infrastructure to provide a more economical alternative to brand-new systems (Akuffo et al., 2004).

1.2 Research Gap

Current literature provides extensive data on standalone DC cooling, but there is a lack of detailed technical research regarding the conversion of existing AC refrigerators into solar-DC hybrids (Brew-Hammond et al., 2001). Retrofitting could reduce costs and promote local fabrication, yet technical challenges (e.g., compressor compatibility, ECU configuration)

remain underexplored. Therefore, this study addresses that gap by exploring these practical challenges through the development and evaluation of a functional retrofitted DC system.

1.3 Objectives

This research was driven by a set of interconnected aims. The primary objective was the development and demonstration of a practical retrofit technique for converting an AC refrigerator to solar-DC operation. Following this, the study aimed to conduct a comprehensive evaluation of the system's energy saving potential, cooling performance, and overall cost-effectiveness. Further objectives included quantifying the project's environmental impact via CO₂ emission reductions and validating its technical reliability through experimental data complemented by a thermodynamic model. Finally, the work aimed to translate these findings into concrete strategies for scalable deployment in developing regions.

2. SYSTEM DESIGN OVERVIEW

This study retrofitted a conventional 112L Haier Thermocool HR-137 refrigerator. The core modification was the installation of a ZH15G variable speed DC compressor, rated at 1.5 A with a COP of 1.2. The new DC power setup consisted of a 300W monocrystalline solar panel, an Stornergy 20A MPPT controller, and a 75Ah Amaron deep-cycle battery. An Electronic Control Unit (ECU) provided system regulation, and the compressor was charged with R134a refrigerant to a pressure of 5 kg/cm². For precise measurement, equipment such as a Mextech LCD Digital

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Website:
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DOI:
10.26480/jtin.01.2025.28.32

Thermometer ($\pm 0.1^\circ\text{C}$ accuracy) and a Meatrol ME440 Power Analyzer ($\pm 0.5\%$ accuracy) were used, along with a pressure gauge ($\pm 0.1 \text{ kg/cm}^2$ accuracy).

Table 1: System Components

Component	Specification	Purpose
Solar panel	300W, Monocrystalline	Capture solar energy
MPPT Controller	Stornergy, 20A	Maximizes charge efficiency
Battery	Amaron, 12V, 75Ah	Energy storage
Compressor	ZH15G DC, 1.5A, 1.5m ³ /h, COP= 1,2	Cooling engine
Refrigerant	R134a, 5 kg/cm ³	Heat exchange medium
Electronic control unit	Integrated with thermostat/fan control	System regulation
Measurement Tools	Mextech Thermometer, ME440 Analyzer, pressure gauge	Monitors performance

2.1 Retrofit Process

The conversion followed a defined technical sequence. Initial attempts to configure the Electronic Control Unit (ECU) revealed a critical start-up challenge. When connected directly to the battery—bypassing the original fan and thermostat—the compressor failed to activate. This problem was resolved by short-circuiting the ECU's C/T terminals, a modification that successfully initiated compressor operation and allowed the system to run correctly without these original components. For the final power system integration, the 300W solar panel was wired to the MPPT charge controller and then to the battery, which supplied the ECU and compressor, thereby establishing a complete 12V DC circuit.

2.2 PV System and Battery Sizing

System power was designed around the energy profile of the ZH15G compressor, which draws 18 W for roughly 10 hours daily, establishing a 180 Wh baseline load. Southern Nigeria's solar resource, with a daily average of 4.5 peak sun hours, served as the primary design constraint (Oniyeburutan et al., 2020). The necessary photovoltaic (PV) capacity was determined by dividing the daily load by this sun-hour value and incorporating a 25% safety factor for real-world losses like soiling and less-than-ideal tilt, giving a nominal requirement of 50 W. To provide a robust margin for consistent charging and future load expansion, a 300W monocrystalline panel was installed. For energy storage, the calculation targeted a usable capacity equal to the daily load at the system's 12V nominal voltage, assuming batteries would not be discharged beyond 50% of their total capacity. This yielded a 30 Ah requirement. A 75Ah deep-cycle battery was selected to provide multiple days of backup operation during periods of low irradiance, ensuring reliable refrigeration.

2.3 Experimental Procedure

Performance was evaluated through controlled cooling tests and direct power measurements. For cooling tests, the retrofitted refrigerator's cabinet was first equilibrated to a uniform 25°C . Its internal temperature was then tracked at one-minute intervals with a Mextech digital thermometer until the minimum stable temperature was achieved. This protocol was repeated three times, with data presented as mean \pm standard deviation. Concurrently, a Meatrol ME440 power analyzer logged the electrical input for both systems. The original AC unit drew 0.84 A at 220 V, translating to 184.8 W of power and a daily energy use of 2.2176 kWh over a 12-hour cycle. In contrast, the retrofit's DC compressor operated at 1.5 A and 12 V, consuming just 18 W. Over its 10-hour daily runtime, this resulted in a total consumption of 180 Wh. To contextualize the energy efficiency within thermodynamic performance, the Coefficient of Performance (COP) was determined. Using the standard relation $COP = \frac{Q_{ref}}{W_{input}}$, and with Q_{ref} for the ZH15G compressor interpolated from manufacturer data at 2400 rpm as 21.6 W, the COP was calculated for

direct comparison with the AC system.

The statistical significance of differences in cooling temperature and energy consumption between the AC and DC systems was evaluated. a paired t-test (significant threshold: $p < 0.05$) performed in SPSS v.26 confirmed whether the measured performance gaps were reliable.

2.4 Thermal Modeling

A lumped capacitance model validated cooling performance:

$$T(t) = T_\infty + (T_0 - T_\infty) \times e^{-\frac{t}{\tau}} \quad (1)$$

Where T_0 represents the initial temperature of 25°C , and T_∞ denotes the achieved steady-state temperature of -3.2°C .

$$T = \frac{pc_pV}{hA} \quad (2)$$

$$T \approx 15\text{min (time constant)}$$

The model was parameterized with the following values: air density (ρ) of 1.2 kg/m^3 , specific heat capacity (c_p) of $1005 \text{ J/kg}\cdot\text{K}$, enclosure volume (V) of 0.09 m^3 , surface area (A) of 0.9 m^2 , and a convective heat transfer coefficient (h) of $8 \text{ W/m}^2\cdot\text{K}$. Using these inputs, the lumped capacitance model predicted a temperature of -2.7°C at the 9-minute mark. This prediction closely aligned with the experimentally measured value of $-3.2^\circ\text{C} \pm 0.3^\circ\text{C}$, thereby confirming the accuracy of the thermal design and the validity of the modeling approach.

3. RESULTS

3.1 Cooling Performance

The DC system cooled from 25°C to $-3.2^\circ\text{C} \pm 0.3^\circ\text{C}$ in 9 minutes, compared to $-4.0^\circ\text{C} \pm 0.2^\circ\text{C}$ in 8 minutes for the AC system (Table 2, Figure 1). Paired t-tests showed no significant difference in final temperatures ($p = 0.08$).

Table 2: Temperature Readings Over Time

Time (min)	DC Temp ($^\circ\text{C}$)	AC Temp ($^\circ\text{C}$)
0	25.0 ± 0.1	25.0 ± 0.2
1	20.0 ± 0.2	23.5 ± 0.2
2	15.5 ± 0.3	19.8 ± 0.2
3	8.0 ± 0.2	15.3 ± 0.3
4	5.0 ± 0.2	11.3 ± 0.2
5	2.5 ± 0.3	7.9 ± 0.2
6	0.5 ± 0.2	4.5 ± 0.3
7	-1.5 ± 0.2	0.8 ± 0.2
8	-2.5 ± 0.3	-3.7 ± 0.2
9	-3.2 ± 0.3	-4.0 ± 0.2

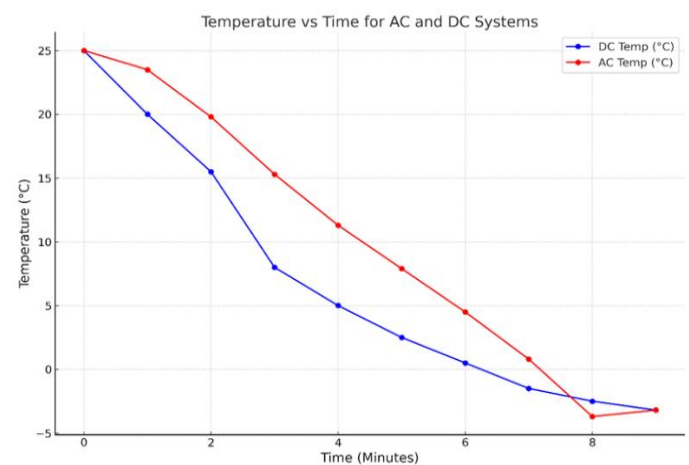


Figure 1: Cooling Profile

Description: Line graph plotting temperature ($^\circ\text{C}$) vs. time (min) for DC (dashed line) and AC (solid line) systems under no-load conditions. DC reaches -3.2°C in 9 minutes, AC -4.0°C in 8 minutes.

3.2 Energy Efficiency

The DC system consumed 0.18 kWh/day, compared to 2.2176 kWh/day for the AC system, yielding 91.88% energy savings (Table 3, Figure 2). Annual usage was 65.6 kWh (DC) vs. 809.4 kWh (AC). Energy savings were significant ($t(12) = 10.32, p < 0.001$).

System	Daily Use (kw/day)	Annual Use (kWh/Year)
AC	2.2176	809.4
DC	0.18	65.6

Energy Savings:

$$\frac{2.2176 - 0.18}{2.2176} \times 100 \quad (3)$$

Energys savings = 91.88%

The 91.88% energy saving notably exceeds ranges reported for standalone DC units (19 - 44% by Anane, 2015). This superior performance stems from the integrated system design, which pairs a smaller, lower compressor with a direct solar power pathway, thereby eliminating inverter losses entirely.

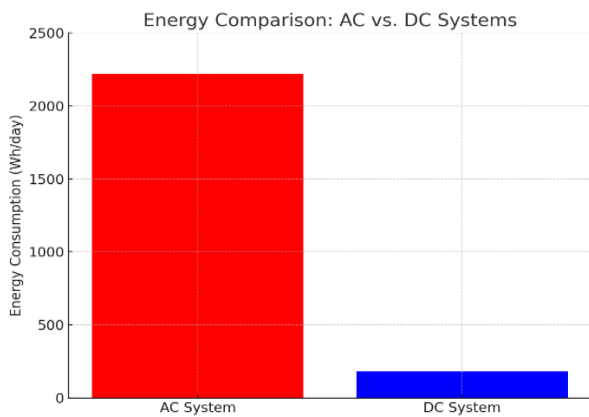


Figure 2: Energy Comparison

Description: Bar chart comparing daily energy consumption (2.217.6 Wh) vs. DC (180 Wh), highlighting 91.88% savings.

3.3 COP Comparison

The DC system's COP was 1.2, vs. 1.3 for the AC system (Figure 3). Despite the lower COP, the DC's 18 W input (vs. 184.8 W for AC) enhanced efficiency.

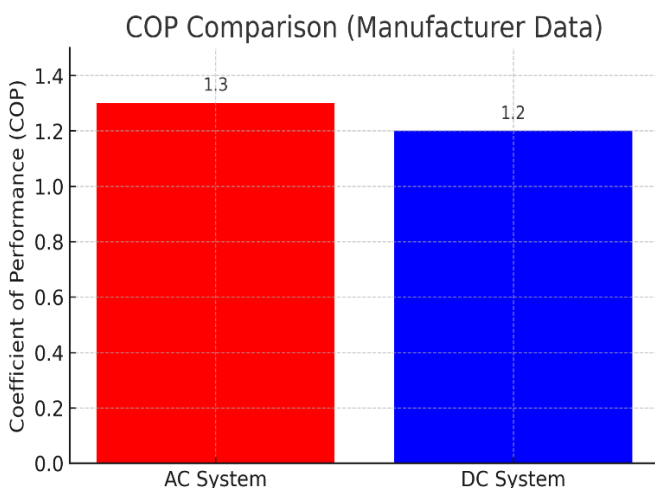


Figure 3: COP Comparison

Description: Bar chart showing COP values for AC (1.3) and DC (1.2), based on manufacturer data.

3.4 Economic Analysis

An economic analysis comparing the retrofit to a new DC unit revealed significant cost advantages. The upfront investment for the conversion was ₦310,000, which is 36.7% lower than the ₦489,993 price of a comparable new DC refrigerator (Table 4). This cost includes ₦165,000 for the solar power subsystem (₦70,000 panel, ₦20,000 MPPT controller, ₦75,000 battery). Factoring in one battery replacement after five years (₦75,000) prorated over the decade, the total 10-year cost of the DC system is projected at ₦240,000. In contrast, operating the original AC system on grid electricity would incur an annual cost of ₦505,890 (based on 2.2176 kWh/day at ₦62.5/kWh), amounting to ₦505,890 over the same 10-year period. The DC system's estimated annual maintenance is ₦11,250, comprising ₦5,000 for routine battery care and ₦7,500 allocated for the future replacement. The calculated simple payback period for the additional solar setup investment (₦165,000) against the annual utility savings, net of maintenance, is approximately 3.55 years.

Component	Cost (₦)
AC cabinet(112-litres capacity thermocool)	145,000
DC compressor	150,000
Accessories/Labour	5,000
Installation	10,000
Total (Conversion)	310,000
New DC refrigerator	489,993
Solar setup	165,000
Battery replacement	75,000
Total (10-year DC)	240,000

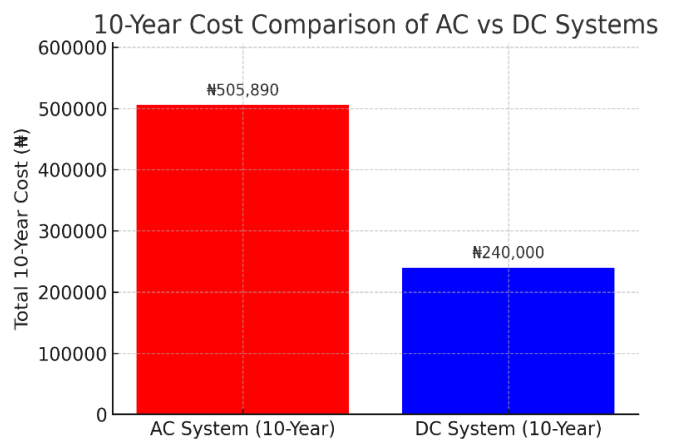


Figure 4: Cost Comparison

Description: Bar chart comparing 10-year costs of AC (₦505,890) and DC (₦240,000) systems, including solar setup and battery replacement.

3.5 Environmental Impact

In addition to energy savings, the retrofit offers a clear environmental benefit. By avoiding the consumption of 743.7 kWh of grid electricity annually, the system reduces associated carbon dioxide emissions. Using a standard emission factor of 0.4 kg CO₂ per kWh for the Nigerian grid, this equates to a reduction of 297.49 kg of CO₂ each year.

4. PERFORMANCE SUMMARY

The retrofitted system prioritizes exceptional energy economy over marginal speed advantages, a design philosophy well-suited to off-grid

environments. It delivers adequate cooling for preservation needs while realizing a drastic 91.88% reduction in daily energy use. Although the DC system's Coefficient of Performance (COP) of 1.2 is numerically lower than the AC unit's 1.3, this is offset by its 90% lower power draw, making it inherently more efficient for photovoltaic power sources. The close agreement between the thermal model's prediction (-2.7°C) and experimental results (-3.2°C) confirms the design's thermodynamic reliability.

4.1 Comparison with Literature

The magnitude of energy savings achieved here (91.88%) substantially surpasses the 25% improvement benchmarked by Sabry and Ker (2020) for conventional DC systems. This dramatic enhancement can be directly traced to two design decisions in the retrofit design: the complete avoidance of inverter-associated losses, estimated at (5–15%, Linquip, 2023) and the precise, demand – responsive operation enabled by the VSDC compressor. When contextualized within existing research, the results reveal a clear trade-off. Prior work establishes a baseline for DC efficiency gains (10-12%, Bilgili 2011) and higher COPs for larger compressors (2.5–3.5 achieved by Ekren et al. 2013). This study's design choice –prioritising a smaller, lower-power compressor within an integrated solar-DC system– navigates this trade-off by maximizing absolute energy savings, a metric more critical than COP alone for off-grid, resource-constrained application.

4.2 Implementation Feasibility

The retrofit's cost (₦310,000) was 36.7% lower than a new DC refrigerator, with a 3.55-year payback and ₦240,000 10-year cost (vs. ₦505,890 for AC). Using locally sourced components enhances accessibility in Nigeria. Applications include healthcare cold chains, rural markets, and vaccine storage, addressing energy poverty. Community training, as suggested by Akuffo et al. (2004), could facilitate adoption. Government subsidies or microfinance could offset the ₦165,000 solar setup cost, making the system viable for low-income households.

Beyond retrofiting, an alternative and potentially more cost-effective strategy would be to import refrigerator cabinets without pre-installed AC compressors. These cabinets could then be locally fitted with compatible DC compressors and refrigerants, enabling flexible customization of solar-powered refrigeration systems for diverse off-grid applications. Such an approach would eliminate the need to purchase complete AC refrigerators solely for conversion, thereby significantly reducing upfront costs. Moreover, localized assembly of these systems would not only enhance affordability but also promote capacity building and small-scale manufacturing within underserved regions, ultimately facilitating large-scale adoption and long-term sustainability.

4.3 Limitations

The ZH15G compressor's 1.5 m³/h capacity limited cooling speed and COP, reducing performance for larger loads. A ZH65G compressor (3.0 m³/h) could increase COP to ~2.0, based on Ning et al. (2021). ECU misconfigurations (e.g., short-circuiting C/T terminals) caused 10–15% efficiency losses until corrected. Solar irradiance variability (4.0–5.5 kWh/m²/day) reduced output by up to 20% on cloudy days, necessitating oversized panels or hybrid systems. The ₦165,000 solar setup cost remains a barrier, requiring policy interventions.

4.4 Future Directions

Future work should test larger compressors (e.g., ZH65G) and hybrid solar-wind systems to ensure reliability. Field trials in diverse climates (e.g., northern Nigeria's 6.0 kWh/m²/day) would validate scalability. IoT-enabled controllers could optimize energy use, reducing maintenance costs by 5–10% annually. Local manufacturing, as proposed by Brew-Hammond et al. (2001), could lower costs by 20–30%. Transitioning to low-GWP refrigerants (e.g., R290) aligns with global standards (UNEP, 2023). Policy frameworks incentivizing solar refrigeration adoption could accelerate deployment in sub-Saharan Africa.

5. CONCLUSION

This research demonstrates that retrofitting conventional refrigerators with solar-DC technology can cut daily energy consumption by 91.88% while providing a 36.7% cost advantage over new DC units. Validation via thermal modelling underscores the technical soundness of this approach. The resulting reduction in both operational expense and CO₂ emissions provides a tangible pathway to improve energy access (SDG 7) and climate action (SDG 13) in off-grid communities, directly supporting food security and healthcare through reliable cooling.

RECOMMENDATIONS

To advance this technology, several strategic recommendations emerge. Future implementations should consider adopting larger VSDC compressors (e.g., ZH65G) to improve cooling capacity and Coefficient of Performance (COP). System resilience can be enhanced by deploying hybrid solar-wind setups to counter intermittency in solar irradiance. To improve accessibility, policy measures such as government subsidies and microfinance schemes are needed to overcome upfront cost and barriers.

ACKNOWLEDGMENTS

The author thanks Prof. Samuel Azi for mentorship and resources, Prof. Aigbogun for departmental support, and the UNIBEN Cooling Unit for technical assistance.

REFERENCES

- Akuffo, F. O., Edwin, I., Forson, F. K., Agbeko, K., Sunnu, A., and Brew-Hammond, A. 2004. Solar Energy Resource Assessment for Ghana. *Journal of the Ghana Institution of Engineers*, 2(1), 31–34.
- Alanne, K., and Saari, A. 2006. Distributed energy generation and sustainable development. *Renewable and Sustainable Energy Reviews*, 10(6), 539–558.
- Anane Solomon Kofi 2015. Development of an Energy Efficient Stand-Alone Solar Photovoltaic DC Refrigerator for Off-Grid Communities. Master's Thesis, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana.
- Apra, C., Mastrullo, R., and Renno, C. 2006. Experimental analysis of the scroll compressor performances varying its speed. *Applied Thermal Engineering*, 26, 983-992.
- Bilgili, M. 2011. Hourly simulation and performance of solar electric-vapor compression refrigeration system. *Solar Energy*, 85, 2720–2731.
- Binneberg, P., Kraus, E., and Quack, H. 2002. Reduction in Power Consumption of Household Refrigerators by Using Variable Speed Compressors. *International Refrigeration and Air Conditioning Conference*, Paper 615.
- Brew-Hammond, A., Edjekumhene, I., and Amadu, M. B. 2001. Preserving and enhancing public benefits under power sector reform: The case of Ghana. *Energy for Sustainable Development*, 5(2), 31–37.
- Btek Renewable Energy. 2000. Sizing battery bank. Retrieved on January 8, 2025, from <http://www.btekenegy.com/documents/215.html>.
- Cengel, A. Y., and Boles, M. A. 2006. *Thermodynamics: Engineering Approach* (5th ed.). McGraw-Hill.
- Ekren, O., Serdar, C., Brad, N., and Ryan, K. 2013. Performance evaluation of a variable speed DC compressor. *International Journal of Refrigeration*, 36, 745-757.
- Incropera, F. P., DeWitt, D. P., Bergman, T. L., and Lavine, A. S. 2007. *Fundamentals of Heat and Mass Transfer* (6th ed.). Wiley.
- Linquip. 2023. Efficiency of inverters: How much power is lost? Linquip Blog. Retrieved January 28, 2025, from <https://www.linquip.com/blog/efficiency-of-inverter/>

- Oniyeburutan, E., Otuoze, A. O., and Abdulkareem, A. 2020. Assessment of Solar Energy Resource in Niger Delta: Case Study Port Harcourt and Yenagoa. *International Journal of Science and Engineering Applications*, 9(2), 12–19.
- Punch. 2024. National grid collapses 12th time in 2024. Retrieved on January 28, 2025, from <https://punchng.com/just-in-national-grid-collapses-12th-time-in-2024/>.
- Sabry, A. H., and Ker, P. J. 2020. DC environment for a refrigerator with variable speed compressor; power consumption profile and performance comparison. *IEEE Access*, 8, 147973-147982.
- Saidur, R., Masjuki, H. H., and Jamaluddin, M. Y. 2009. Energy and environmental benefits of using variable speed compressors in refrigeration systems. *International Journal of Green Energy*, 6(1), 65-72.
- United Nations. 2015. Sustainable Development Goals (SDGs). Retrieved on January 28, 2025, from <https://www.un.org/sdgs>.
- World Bank. 2021. Nigeria to improve electricity access and services to citizens. World Bank Press Release. Retrieved January 28, 2025, from <https://www.worldbank.org/en/news/press-release/2021/02/05/nigeria-to-improve-electricity-access->

