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Original Research Article

Evaluating the Performance and Applicability of Solar-Powered Absorption Refrigerators in High-Temperature Rural Regions of Kenya.

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ABSTRACT

Access to reliable cooling services remains limited in off-grid, arid regions, despite their high solar energy potential. In sub-Saharan Africa, only a small fraction of farmers have access to reliable cold storage, and conventional refrigeration often relies on electricity and refrigerants with high ozone depletion potential or global warming potential. Solar-powered absorption refrigerators, which utilize thermal energy instead of compressors and non-toxic refrigerants, provide a cleaner alternative. This study examined a 30-L single-effect solar-vapor absorption refrigerator (with 25kg capacity) using cyclopentane as the refrigerant. The system was powered by a 350W photovoltaic panel, a battery (12V, 200Ah), a Direct Current heater, and a controller. Field tests were conducted in off-grid Turkana, Kenya, under two scenarios: a no-load (empty cabinet) scenario and a realistic load (bottled water) scenario. Temperatures at the generator, evaporator, condenser, cabinet, and ambient were logged, and solar irradiance was measured. From this data, the cooling Coefficient of Performance (COP) and system efficiency were calculated. Under no-load, the cabinet reached 4.3°C (from 36°C ambient) and achieved a COP of 0.091; under load, the cabinet reached 8.6°C with a COP of 0.105. The system efficiency was 78.6%. These results demonstrate that even with modest input power, the solar-driven absorption refrigerator can maintain temperatures above freezing, suitable for vaccine or food storage in off-grid communities.

KEYWORDS

Solar cooling, Vapor Absorption Refrigeration, Coefficient of Performance (COP), Off-grid refrigeration.

INTRODUCTION

The global demand for cooling is rapidly increasing, particularly in tropical regions. In sub-Saharan Africa, rising incomes and recurrent heat waves are increasing the refrigeration needs of homes, farms, and clinics.

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However, access to reliable cooling remains limited, with only 12% of African farmers having access to cold storage [1]. This increased demand for cooling is already placing tremendous stress on energy infrastructure and increasing emissions. Alternative technologies for clean and efficient cooling are critical to address these concerns [2]. Generally, hot climatic conditions have a high demand for cooling; therefore, energy is required. Cooling in hot climatic conditions is primarily achieved using conventional refrigeration systems, which often demand a high share of building electrical energy [3]. In addition to the high energy demand for cooling, the cost of energy is the most often used conventional refrigerators employing chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs) [2]. However, these refrigerants have raised concerns due to their ozone depletion potential (ODP) and global warming potential (GWP). Therefore, cooling is a blind spot in energy access and climate policy: it sits at the intersection of clean energy, food security, health, and the Kigali Amendment on HFC phase-down [4].

In Kenya, climate change and development plans underscore these challenges. Turkana County (northern Rift Valley) is one of Kenya's hottest zones (monthly peaks ≈40 °C with sparse electric infrastructure) [5]. The National Vision 2030 and Green Industrialization strategy aim to expand access to clean energy and reduce GHG emissions by 30% by 2030 [4]. However, conventional cooling systems use HFC refrigerants and diesel generators, undermining these goals. To address this, Kenya launched a National Cooling Action Plan targeting high-efficiency appliances, low-global-warming refrigerants, and broader cold-chain access. Solar-driven absorption systems are a promising solution as they use free solar heat and benign working fluids (e.g., NH_3–H_2O with zero ozone depletion potential) [6].

Absorption refrigeration systems have been widely studied for solar cooling, which has a simple system form and a high coefficient of performance. Numerous studies have analysed solar-powered absorption coolers, often via modelling or lab prototypes [7] and most research absorption cooling has been mainly focused on either NH_3–H_2O and LiBr-H2O use as a working fluid [8,9]. However, most existing studies are based on simulations or controlled laboratory experiments, with limited attention given to real-world field evaluations. In particular, empirical assessments of low-cost absorption refrigeration systems using cyclopentane (a more environmentally friendly refrigerant) under real off-grid climatic conditions remain scarce. This lack of field-based evidence represents a significant research gap, especially in rural regions of Kenya where decentralized cooling solutions are critically needed.

This experimental paper closes in on the gap by reporting on a field evaluation of a solar-powered absorption refrigeration system in Turkana region. The objective of this study is to evaluate the performance of a solar-powered absorption refrigeration system to determine its applicability in hot and dry conditions and encourage its implementation as a means of addressing energy and cooling challenges in off-grid areas and curbing the effects of climate change by using cyclopentane as a refrigerant and solar energy resource.

Working principle of Absorption Refrigerators

Absorption refrigeration is a cooling method that uses a thermochemical process with an absorbent and refrigerant instead of mechanical compression [10]. The absorption refrigeration cycle as shown in Figure 1, is the fundamental thermodynamic cycle involved, which consists of four major processes: evaporation, absorption, desorption, and condensation [11]. In this cycle, a refrigerant evaporates, collecting heat from the surroundings and producing a cooling effect. The vaporized refrigerant is absorbed by a secondary fluid (absorbent), such as water or lithium bromide, resulting in a solution. This solution is heated in the generator, causing the refrigerant to evaporate and then condense back into a liquid to complete the cycle [12].

There are two basic types of absorption cooling systems: single-effect and double-effect systems. Single-effect absorption chillers, which use a single generator, are simpler and less expensive but are less efficient. Double-effect absorption chillers with two generators increase efficiency by better utilizing heat, resulting in greater coefficients of performance (COPs) [13]. The COP, a measure of energy efficiency, is frequently used to evaluate the effectiveness of an absorption cooling system. The coefficient of performance is defined as the ratio of the cooling effect to the thermal energy input [11]. Although absorption cooling systems have lower COPs than standard vapor-compression systems, their energy efficiency can be improved by carefully designing and selecting working fluids. In addition to the COP, the energy efficiency of the system is affected by the performance of each component in the thermodynamic cycle, such as heat exchangers, generators, and absorbers.

COP is not the only performance indicator used to evaluate absorption cooling systems. Another important indicator is the Energy Efficiency Ratio (EER), which like COP, is adjusted for specific conditions and is frequently used to assess the energy efficiency of cooling systems under various operational scenarios. The Coefficient of Performance (COP) in absorption cooling systems typically ranges between 0.6 and 1.2, depending on the design and operational conditions [14]. Absorption cooling low COPs can also be considerably increased by optimizing the thermodynamic cycle, such as by adopting double-effect designs that use heat better. The double-effect absorption system comprises two stages of generation, which boosts the overall efficiency and COP [15].

Entropy and exergy evaluations are essential for a better understanding of the thermodynamic efficiency of absorption cooling systems. Entropy analysis aids in finding the irreversibilities within the cycle responsible for efficiency loss. Entropy creation can be reduced to increase the overall system efficiency. Exergy analysis, on the other hand, assesses the quality of energy and its capacity to perform work [16]. It identifies where energy deterioration occurs in the system and aids in modifying the design to reduce energy losses. Exergy analysis is particularly effective in analyzing the performance of absorption cooling systems because it considers both the quantity and quality of energy fluxes, resulting in a more complete assessment of system performance.

The efficiency of these systems is also determined by the working pairs utilized, which include lithium bromide-water (LiBr-H2O) and ammonia-water (NH3-H2O). LiBr-H2O systems are commonly used for large-scale air conditioning, whereas NH3-H2O systems are appropriate for a broader range of applications, including refrigeration and air conditioning

[17]. Despite their benefits, solar-powered absorption cooling systems must be more efficient and cost-effective to compete with traditional cooling technologies.

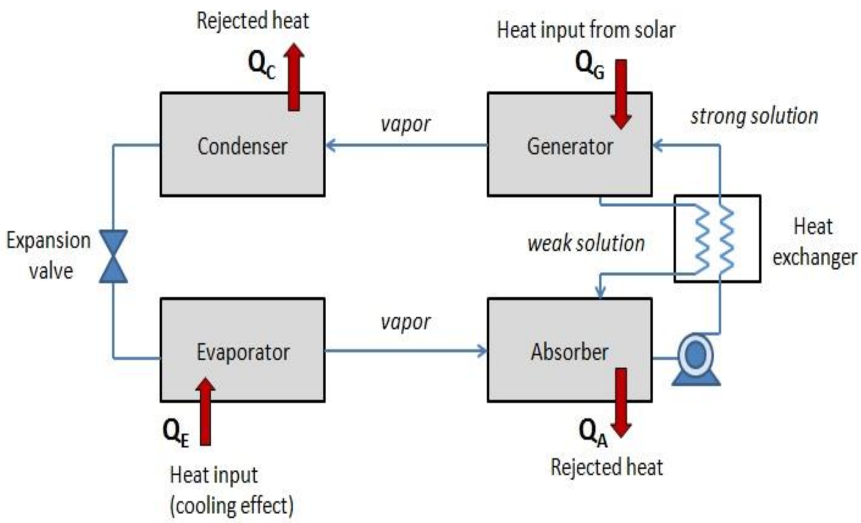

Figure 1. Working Principle of Absorption Refrigeration System

MATERIALS AND METHODS

The study was conducted in off-grid Turkana County (Kenya), a hot, arid region where decentralized solar cooling is critical. An experimental solar vapor absorption refrigeration (VAR) system was assembled, comprising a 350 W rooftop photovoltaic panel, 30 A charge controller, a 12 V battery (200 Ah), a 25 A DC heating element, and a 30-L single-effect absorption refrigeration unit (using cyclopentane as the refrigerant). Actual schematic design of the whole solar-powered vapor absorption refrigeration system is shown in Figure 2. Cyclopentane was chosen for its environmental benefits: it has zero ozone-depletion potential and negligible global warming potential. Multiple digital temperature sensors were placed at key locations: inside the generator, evaporator, condenser, refrigerated cabinet, and ambient (outside). Factory-calibrated sensors (DS18B20) with quoted accuracy ±0.5 °C were used. Sensors were calibrated via a two-point method (ice-point and a reference thermometer) before deployment to ensure traceability. Ambient solar irradiance was measured with a pyranometer (accuracy within 5%).

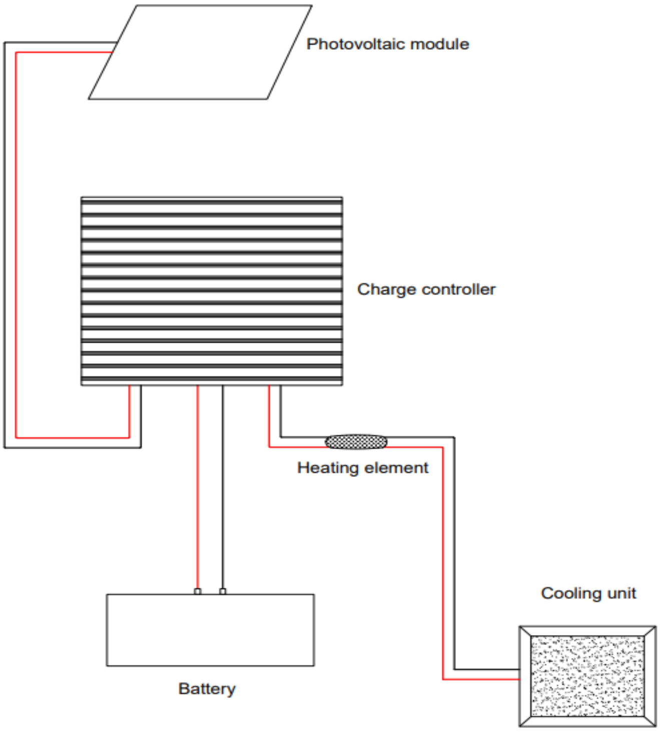

Figure 2. Actual schematic design of the whole solar-powered vapor absorption refrigeration system.

The experimental procedure involved two test scenarios. In the no-load tests as shown in Figure 3, the insulated cabinet was empty, and temperatures were logged from sunrise to evening. In the load tests, bottles of water were placed in the cabinet to simulate cooling a perishable load. In each case, ambient temperature and solar irradiance were recorded alongside component temperatures at regular intervals. Key performance metrics were calculated from these data: the coefficient of performance (COP), defined as the ratio of heat removed from the cabinet to the thermal energy input at the generator, and the system efficiency ratio (η), defined as the COP divided by the ideal (Carnot) COP at those temperatures. These metrics quantify the cooling power and overall efficiency of the system. In calculating the COP and the system efficiency ratio (η), 错误!未找到引用源。 and Equation (2) are used like that achieved in the studies of Mogaji *et al* and Akinola *et al* [18,19].

$$COP = \frac{T_e}{T_g} \tag{1}$$

$$n = \frac{COP}{COP_c} \tag{2}$$

Where the term T_e = the average evaporator temperature, T_g= average temperature of the generator and Carnot coefficient of performance (COP_c) in Equation (2) is obtained using Equation (3)

$$COP_c = (\frac{T_g - T_a}{T_g})(\frac{T_e}{T_c - T_e}) \tag{3}$$

Figure 3. Experimental setup of the vapor absorption refrigerator during load testing

Figure 4. Cabinet space of the vapor absorption refrigerator with bottled water

Data was analysed by plotting temperature profiles over time and computing average COP and system efficiency (η) for each test. All measurements and calculations were repeated over several days to ensure reliability. This approach allowed assessment of how the solar VAR system performs under realistic Turkana conditions and how it meets the cooling demands identified in the survey conducted.

RESULTS

Local Cooling Needs Assessment

A survey of Turkana households, farmers and health facilities revealed substantial unmet cooling requirements. Many farmers reported that extreme heat causes frequent crop spoilage, forcing more than 75% to sell produce immediately after harvest (often at reduced prices) to avoid losses. Roughly 85% of these farmers believed that access to nearby cold storage would improve their income and market leverage. Healthcare facilities similarly face cooling challenges, for example, the local health canter’s labor room lacks air conditioning, and the nearest blood bank is 160 km away.

Vaccines and medicines therefore depend on unreliable distant cold chains, highlighting a need for local solar refrigerators. In homes and public buildings, passive cooling (thick walls, ventilation) and fans are common, but mechanical cooling is rare. Less than 1% of households own any cooler, though about 15–20% expressed interest in solar-powered cooling to improve comfort. These findings underscore a high demand for affordable, off-grid refrigeration for food, vaccines and comfort in Turkana.

System Performance

No-Load Tests Scenario

Under no-load conditions, the VARS generated a clear cooling effect in the empty cabinet. The ambient temperature rose to ~36°C by midday, while the generator temperature climbed to ~180°C as shown in Figure 5. As expected, the condenser temperature also rose, indicating effective heat rejection. The cabinet temperature, however, dropped steadily: it reached a minimum of about 4.3°C by the sixth hour (around 11 am) before slowly rising again as the heat input waned. This confirms that the system can maintain the cabinet well above freezing (4–5°C) even under peak heat. In line with other studies, these results indicate that the solar VAR can sustain a cold environment for several hours with no external load. The above-freezing cooling is especially suitable for preserving food and beverages without freezing damage.

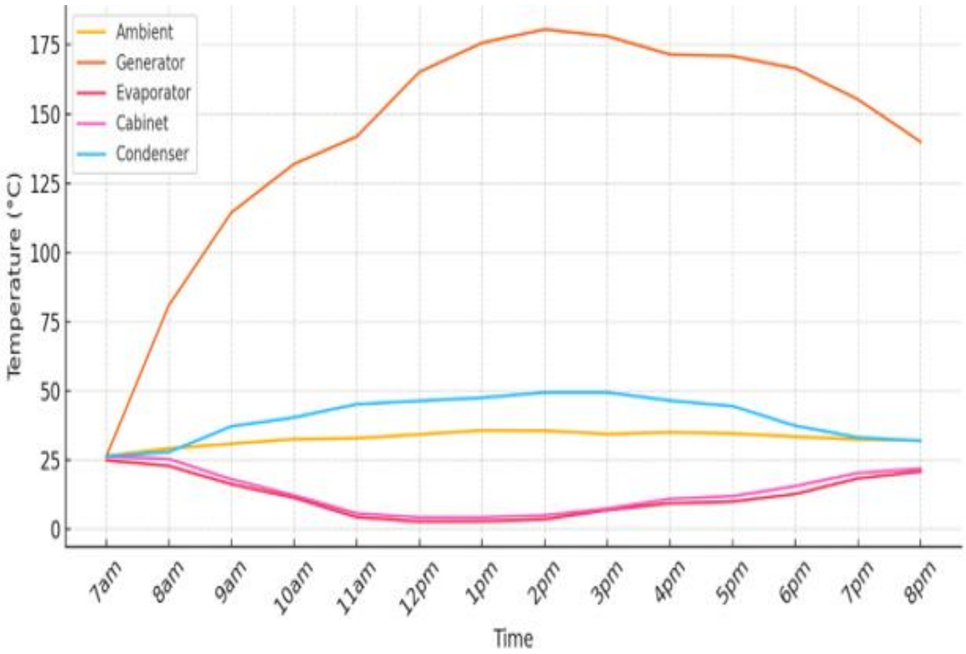

Figure 5. Temperature profile under no-load testing

Loaded Tests Scenario

When cooled water bottles were placed in the cabinet (load conditions), the system still achieved significant cooling. Figure 6 illustrates temperature variation under loaded condition. It shows that the minimum cabinet temperature reached 8.6°C (at about 4 pm). This somewhat higher nadir (compared to 4.3°C empty) reflects the additional heat load of the water. Throughout the day the system maintained the cabinet temperature below ambient (often by >10°C), demonstrating reliable refrigeration. The continuous above-zero cooling implies that beverages or fresh produce could be chilled effectively. Overall, the solar VARS operated dependably all day, confirming that it can deliver useful cooling power in Turkana's climate.

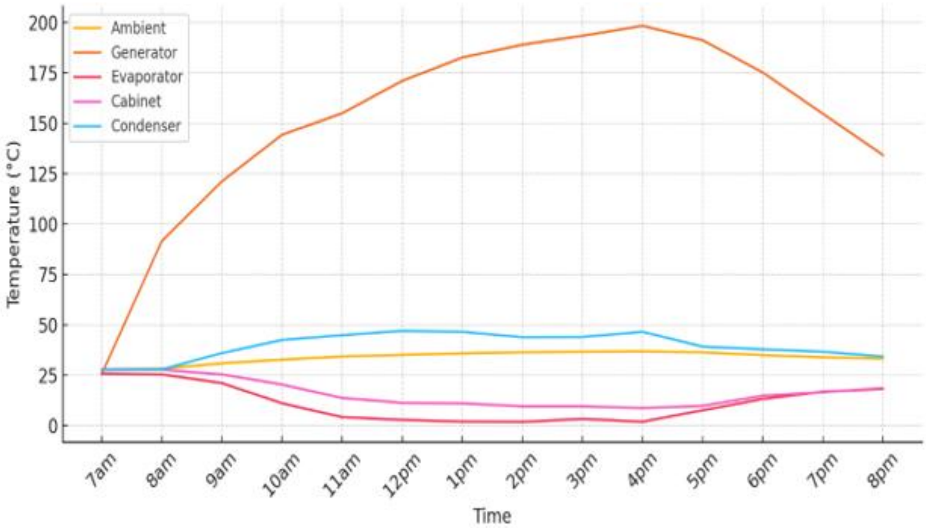

Figure 6. Temperature profile under load testing

DISCUSSION

Implications of Cooling Needs Assessment

The survey results highlight where the solar VAR system can have an impact. In agriculture, the ability to slow spoilage (e.g. cooling vegetables and fruits to ~5–8°C) would allow farmers to store produce longer and sell at better prices. In healthcare, even a small solar-powered refrigerator could provide local vaccine and blood storage, reducing the risk of spoilage due to erratic power. The fact that >85% of farmers and many community members expressed interest in off-grid cooling (for crops, milk, or home comfort) suggests that adoption of a reliable VARS could be high. The system tested meets several key needs: it is powered by abundant sunlight, requires no grid electricity, and achieves above-freezing temperatures suitable for vaccine storage and beverage chilling. In essence, the experimental results show that solar VARS can contribute directly to the principal cooling objectives identified (food preservation, vaccine and thermal comfort).

Thermal Behavior and Flow Patterns

Comparing load vs. no-load tests reveal useful flow dynamics. Under load test, the generator temperature took longer to peak (about 4 hours) than in no-load tests. This delay occurs because additional heat is absorbed in cooling the water load, requiring more energy to drive vaporization of the refrigerant. In both cases, the cabinet and evaporator temperatures followed a similar cooling trend, achieving and maintaining low temperatures as expected. These patterns suggest an annular flow regime in the generator and evaporator: as vapor generation increases, a thin film of refrigerant flows along the tubes, improving heat transfer and sustaining a cold cabinet. Meanwhile, the condenser and ambient temperatures rose steadily after about the first four hours, reflecting a transition from stratified to annular flow in the condenser. This behavior is consistent with the physics of single-effect absorption chillers and matches observations in other studies e.g., Mousavi et al [16], where the onset of strong boiling causes the condenser to reject heat more effectively over time.

Performance Metrics and Comparisons

The calculated COP values for the system were relatively low: approximately 0.091 (no-load) and 0.105 (with load) as shown in Table 1. These mean that only about 9–10% of the input heat energy was delivered as useful cooling. Correspondingly, the system efficiency ratio (η) was about 72% (no-load) and 79% (load) of the ideal Carnot efficiency. Although these COPs are small, this is not unusual for small single-effect solar absorption systems. For comparison, typical single-effect absorption chillers have COPs on the order of 0.7 (at high heat input), while electric compressor chillers often achieve COPs >3. Thus, our measured COP ~0.1 reflects both the low-grade solar heat source and the modest scale of the system. Importantly, even with low COP, the system delivered substantial cooling (water to ~8–9°C) during sunny hours, demonstrating practical viability or rather functional availability of cooling where no other options exist. The higher efficiency ratio under load (78.57% vs. 76.92%) indicates more effective use of the driving heat when the system is actively removing heat. The cooling performance (COP) value obtained for the absorption cooling system in this study is like those observed in the study of Mondal et al [20]. In summary, the performance metrics confirm that objective performance thresholds were met: the system functioned as intended, providing refrigeration powered solely by solar energy, albeit at modest efficiency.

Table 1. Performance summary

Condition	Mean COP	System Efficiency [η]	Minimum Cabinet Temperature [°C]
No-load test	0.0914	76.92%	4.3
Loaded test	0.1052	78.57%	8.6

Using cyclopentane as a refrigerant provided clear environmental benefits: it has zero ozone-depletion potential and a negligible Global Warming Potential (GWP). However, cyclopentane is flammable, which introduces safety considerations that must be addressed during system deployment. For rural applications such as those in Turkana, several low-technology safety measures can reduce potential risks. These include installing the refrigeration unit in well-ventilated outdoor locations, maintaining sufficient distance from open flames or cooking areas and enclosing the system within protective ventilated housings. Regular inspection of tubing connections for leaks and basic user training can further improve operational safety. These measures are feasible in low-resource environments and can significantly mitigate risks associated with cyclopentane.

CONCLUSION

This study confirms that solar-powered absorption refrigeration systems can provide viable off-grid cooling solutions in arid regions. It demonstrated that a modest 12 V, 30 L solar-powered vapor absorption refrigerator can have a profound impact on food security and healthcare in off-grid communities . In tests, it cooled the cabinet to as low as 4.3°C (no load) and 8.6°C (with load) using only solar energy. These temperatures, while above freezing, are well within the range needed for safe beverage and fresh-produce storage in tropical regions. The system's mean COP (~0.1) was low compared to standard chillers, but the refrigeration achieved is sufficient for the intended uses. Importantly, the refrigerator used an eco-friendly refrigerant and relied entirely on renewable energy, aligning sustainability goals. The positive survey response (high demand for local cooling) and the system's reliable operation indicate that solar absorption refrigeration is a viable solution for rural cooling needs. The findings support the deployment of solar thermal cooling technologies to improve cold-chain services in remote and underserved regions.

Future work could focus on optimizing the design (e.g. heat exchangers, hybrid cycles) to improve COP and load capacity, and on developing safety protocols for using flammable refrigerants. For rural applications, several low-technology safety approaches can be implemented, including outdoor installation of refrigeration units, natural ventilation, leak inspection procedures and protective housings to reduce ignition risk.

Overall, the research objectives were met: the solar VAR system was successfully tested under real-world conditions, showing that solar power can reliably drive refrigeration for rural food and vaccine preservation in Turkana region.

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NOMENCLATURE

Symbols

A	ampere
BTU/h	British Thermal Unit per hour
V	voltage
W	wattage

Greek letter

η	efficiency ratio	(%)

Abbreviations

COP	Coefficient of Performance
CFCs	Chlorofluorocarbons
DC	Direct Current
EER	Energy Efficiency Ratio
ESMAP	Energy Sector Management Assistance Program
GHG	Greenhouse Gas
GWP	Global Warming Potential
HFCs	Hydrofluorocarbons
LiBr-H2O	Lithium bromide water
NH3-H2O	Ammonia water

ODP Ozone Depletion Potential
VARs Vapor Absorption Refrigerators

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