Waste Heat Driven Vapour Absorption Refrigeration System for Two-Wheelers Using LiBr-H_2O Pair

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Abstract. With rising urban temperatures and the lack of climate control in two-wheelers, riders particularly in the developing world experience high thermal discomfort. Conventional vapour compression-based systems are not feasible for two-wheelers because of space and power constraints. In spite of widespread work on automotive waste heat recovery, very little work has been done on rider-centric, compact, and sustainable two-wheeler cooling systems. This work fills that void by presenting a new vapour absorption refrigeration system (VARS) using waste energy from a two-wheeler's exhaust gases. The system uses a lithium bromide–water (LiBr-H_2O) couple to provide localized cooling through a wearable jacket-type evaporator. A thermoelectric generator (TEG) additionally adds self-sufficiency by driving the VARS pump, rendering the system almost energy-autonomous in nature. Thermodynamic analysis indicates the maximum COP of 0.944 and practical COP of 0.7365. This paper offers a sustainable and innovative method for enhancing rider comfort without sacrificing the performance of vehicles, offering energy-efficient and climate-resilient transport solutions.

Key words: Vapour Absorption Refrigeration, Two-Wheelers, Waste Heat Recovery, Thermoelectric Generator, LiBr-H_2O, Energy Efficiency

1 Introduction

In light of rising global temperatures, the surge in urban mobility, and swelling environmental pressures, the need for energy-saving and comfort-improving technologies in transport has never been more urgent [1]. Two-wheelers make up a substantial share of daily travels in developing nations, be inclined to expose riders to extreme heat since they do not consist of built-in climate control systems. As opposed to cars, two-wheelers have inherent constraints of usable power, volume, and body strength that discourage the application of traditional vapour compression refrigeration systems (VCRS) [2, 3]. These systems, which are mechanically powered and of high power consumption, offer reduced fuel economy and higher engine load making them less suited for two-wheeled vehicles [4].
Under these conditions, there is a strong demand for compact, low-power, vehicle-independent refrigeration technologies [5]. Vapour absorption refrigeration systems (VARS) represent a good option by converting thermal energy specifically low-grade waste heat directly into work rather than mechanical work [6]. Of the different working fluid pairs, the

lithium bromide–water (LiBr–H_2O) pair is especially notable for its low toxicity and non-flammability, as well as having zero ozone depletion potential. Through the utilization of exhaust heat from internal combustion engines, the VARS cycle can be powered without supplementary fuel use or considerable energy input, converting a generally wasted resource into an effective one [7, 8].
Aly et al.'s [3] study investigated using waste heat from motor vehicle exhaust systems in vapour absorption refrigeration. Their study highlighted the environmental advantages and energy efficiencies possible through such waste heat recovery systems. Mohammadi et al. [4] inspected a solar-powered VAR system for air conditioning purposes. They focused on problems of low-pressure maintenance and recommended design changes to enhance system efficiency. Ajay et al. [9] conducted a thermodynamic simulation for an office cooling single-effect LiBr-H_2O VAR system under the climatic conditions of Ludhiana. The study exhibited that as the room temperature raised from 22°C to 30°C, the coefficient of performance (COP) went up from 0.55 to 0.75, emphasising the sensitivity of the system to ambient conditions. Alfaris et al. [10] evaluated the performance of a LiBr-H_2O VAR system driven by a parabolic trough solar collector. The system generated an average Coefficient of Performance of 0.47, exhibiting the promise of solar energy in powering VAR systems with reference to efficiency optimization considerations. Singh and Verma [11] used artificial neural networks to perform energy analyses of a LiBr-H_2O VAR system. Their method demonstrated precise estimates of thermodynamic properties, showing the effectiveness of ANN in improvement of system performance.

Zhou et al. [12] did an advanced exergy and exergo-economic evaluation of a coupled LiBr-H_2O VAR and organic Rankine cycle system for low-grade heat recovery. It has been found that considerable investment cost reductions are possible by optimizing the system design. Yadav et al. [13] studied the performance of a VAR system for waste heat recovery from internal combustion engines. They emphasised the high potential of the utilization of exhaust heat, which is a huge percentage of energy losses in the engines. Dubey and Arora [14] conducted a parametric study of solar-powered LiBr-H_2O cooling systems for commercial establishments. From their research, they found that the use of such systems would result in up to about 74% energy savings in comparison to conventional electric compression chillers. Staudt et al. [15] created and experimentally validated a control-oriented LiBr-H_2O absorption heat pumping device model. Their research focused on the improvement of modulation and part-load operation, tackling issues in dynamic operating regimes.
The system under consideration in this research is to harness and utilize waste heat from a two-wheeler engine exhaust to power a VARS that provides personal cooling by using a jacket-type evaporator worn by the rider. The idea converts passive thermal loss into active thermal comfort that adds to the well-being of the rider without any reduction in the performance or efficiency of the vehicle. In addition, to provide energy independence, the system has a thermoelectric generator (TEG) that harnesses waste exhaust heat to drive the VARS pump. This integrates a completely autonomous, waste-heat-powered refrigeration system.

In spite of considerable study on automotive waste heat recovery and absorption cooling for buildings and heavy-duty vehicles, there has been extremely minimal research focused on portable, rider-based cooling for two-wheelers. This research fills that knowledge gap by reporting the conceptual design and thermodynamic study of a LiBr–H_2O-based VARS appropriate for miniaturized vehicular platforms. The research not only suggests a new application of known thermodynamic laws but also illustrates the system's efficiency parameters and energy feasibility under actual engine operating conditions.

2 Heat Recovery from Exhaust Gases of a Four-Stroke Single Cylinder CI Engine

In internal combustion engines, even a small percentage of fuel energy is used to produce mechanical work, while a very large amount—about 30–40%—is lost as exhaust waste heat. There is a strong potential for such waste heat recovery and utilization. For the purpose of this project, a four-stroke single-cylinder compression ignition (CI) engine is taken into account and its exhaust heat is utilized to power a lithium bromide-water-based vapour absorption refrigeration system (VARS). To efficiently harness the exhaust heat, one has to estimate the thermal energy that is available based on the operational conditions of the engine and the thermodynamic characteristics of the exhaust gases. The subsequent section gives a step-by-step analytical method of determining the recoverable exhaust heat energy. Engine parameters are discussed in table 1.

Table 1. Engine parameters

Type	Four Stroke, Single Cylinder CI Engine
Power output	4.4 kW
Engine speed	150 RPM
Specific fuel consumption	0.22 kg/kW-hr
Compression ratio	17.5:1
Density of air	1.16 kg/m^3
Specific heat of gases	1.1 kJ/kg.K
Exhaust gas inlet temperature	450°C
Ambient temperature	45°C
Heat exchanger effectiveness	0.85

The heat recovery estimates are aimed at approximating the thermal energy potential of engine exhaust gases for powering the VARS generator. Beginning with the engine's power and specific fuel consumption, the fuel mass flow rate is determined. By applying the swept volume and engine speed, the volumetric flow rate of intake air is obtained, followed by its mass flow rate from air density. The exhaust gas flow rate is derived by adding fuel and air mass flows. Total recoverable heat is calculated using temperature difference between exhaust and ambient air and specific heat capacity. The last step uses heat exchanger effectiveness to calculate usable heat input into the generator. The conclusion verifies that adequate waste heat is generated for refrigeration. These calculations provide an accurate and realistic energy balance for system design. The step by step calculation is discussed as follow.

Step 1: Fuel Mass Flow Rate
The mass flow rate of fuel is calculated using the engine's specific fuel consumption (SFC) and power output:
$\dot{m}_f = SFC \times Power$
$\dot{m}_f = 220$ g/kWh × 4.4 kW = 968 g/h = 968/3600 = 0.269 g/s = 0.000269 kg/s

Step 2: Air in-take Volume Rate
Swept Volume, $V_s = 6.61 \times 10^{-4}$ m^3
Engine Speed, N = 1500 rpm
Volumetric flow rate of air is calculated as:
$Q = (V_s \times N) / 2 = (6.61 \times 10^{-4} \times 1500) / 2 = 0.49575$ m^3/min $= 8.2625 \times 10^{-3}$ m^3/s

Step 3: Air Mass Flow Rate

$\dot{m}_a = \rho_{air} \times Q = 1.16 \times 8.2625 \times 10^{-3} = 0.00959$ kg/s

Step 4: Total Exhaust Mass Flow Rate
$\dot{m}_{exhaust} = \dot{m}_f + \dot{m}_a = 0.000269 + 0.00959 = 0.00986$ kg/s

Step 5: Heat Available in Exhaust Gases
$Q_{exhaust} = \dot{m}_{exhaust} \times C_p \times (T_{exhaust} - T_{ambient})$
$Q_{exhaust} = 0.00986 \times 1.1 \times (450 - 45) = 4.38$ kW

Step 6: Effective Heat Supplied to Generator
$Q_{generator} = Q_{exhaust} \times \eta_{hex} = 4.38 \times 0.85 = 3.72$ kW

3 Design of Vapour Absorption Refrigeration (VAR) System

The configuration of a vapour absorption refrigeration (VAR) system comprises thermodynamic modelling of every component of the system, such as the absorber, generator, condenser, evaporator, solution heat exchanger, and pump. The schematic of VAR is shown in fig. 1.

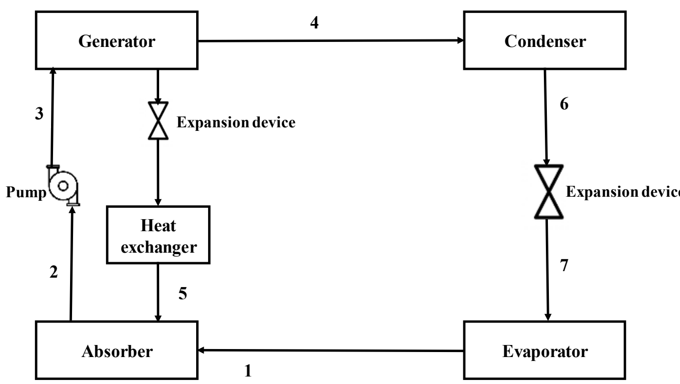

Figure 1 Schematic of VAR system

The refrigerant used in this system is water and the absorbent used is lithium bromide (LiBr). To design a workable VAR system, the most important factor is to find the mass and energy balances at each state point at steady-state conditions. This part describes the sequential modelling process and contains only the basic equations required for design and analysis of the system performance. Major inputs are temperatures, pressures, solution concentrations, and enthalpies. Negligible pressure drops and ideal heat exchangers are assumed where applicable. The design is carried out on a cooling load and accessible waste heat from engine exhaust. Thermodynamic property information is obtained from standard LiBr-H_2O plots and steam tables.

Step 1. Mass balance across absorber :
$\dot{m}_s = \dot{m}_r + \dot{m}_w$
Where, $\dot{m}_s$ = mass flow rate of strong solution, $\dot{m}_r$ = mass flow rate of refrigerant, $\dot{m}_w$ = mass flow rate of weak solution

Step 2. Mass fraction balance :
$\dot{m}_s * X_s = \dot{m}_w * X_w$

Where X_s = LiBr concentration in strong solution, X_w = LiBr concentration in weak solution

Step 3. Energy balance at evaporator :
$Q_e = \dot{m}_r * (h_1 - h_7)$
Where h_1 = enthalpy of refrigerant vapour, h_7 = enthalpy of liquid refrigerant entering evaporator

Step 4. Energy balance at generator:
$Q_g = \dot{m}_s * h_3 – (\dot{m}_r * h_4 + \dot{m}_w * h_5)$
Where, h_3 : Enthalpy of strong solution entering generator
h_4: Enthalpy of refrigerant vapour exiting generator and entering condenser
h_5: Enthalpy of weak solution exiting generator and returning to absorber

Step 5. Energy balance at condenser:
$Q_c = \dot{m}_r * (h_4 - h_6)$
Where h_6: Enthalpy of liquid refrigerant exiting condenser and entering evaporator
Step 6. Energy balance at absorber:
$Q_a = \dot{m}_r * h_1 + \dot{m}_w * h_5 - \dot{m}_s * h_2$

Step 7. Pump work:
$W_p \approx \dot{m}_s * (P_g - P_a) / \rho$
Where P_g = pressure at generator, P_a = pressure at absorber, ρ = density of solution

Step 8: COP of the system:
$(COP)_{actual}$ = Refrigerating effect/Work input
$(COP)_{actual} = Q_e / (Q_g + W_p)$

4 Results & Discussion

The effectiveness of a vapour absorption refrigeration system (VARS) is highly influenced by the operating temperatures of its main elements and internal heat exchange effectiveness. This chapter shows the influence of altering generator, condenser, evaporator, and absorber temperatures on the COP. It also examines how the heat exchanger effectiveness and variations in pump work influence system performance. System performance under different operating parameters are evaluated to extract engineering insights. The conclusions are based on theoretical modelling and substantiate the viability of waste heat utilization for cooling. The effect of each parameter is critically estimated to determine optimal design and operating ranges.

4.1 Effect of Variation in Generator Temperature on COP:

Figure 2 represents variations in COP with generator temperature. Since the temperature of the generator varies in the range of 90°C to 115°C, the reversible COP shows a improving trend, which is about a 20% rise, while the theoretical COP decreases by about 8%. This phenomenon happens since increasing generator temperatures improve the separation of the refrigerant from the absorbent but raise irreversibility with greater temperature gradients. Above 110°C, the performance declines due to redundant thermal energy that does not create useful work and increases exergy destruction. Thus, there exists an optimal generator temperature (~105°C) that optimizes energy input versus effective refrigeration. This knowledge helps to ensure maximum system efficiency without suffering from excessive thermal stress.

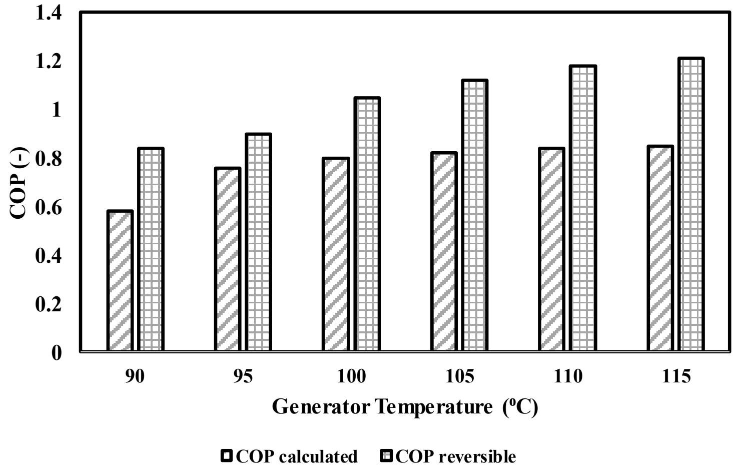

Figure 2. Variation in COP with generator temperature

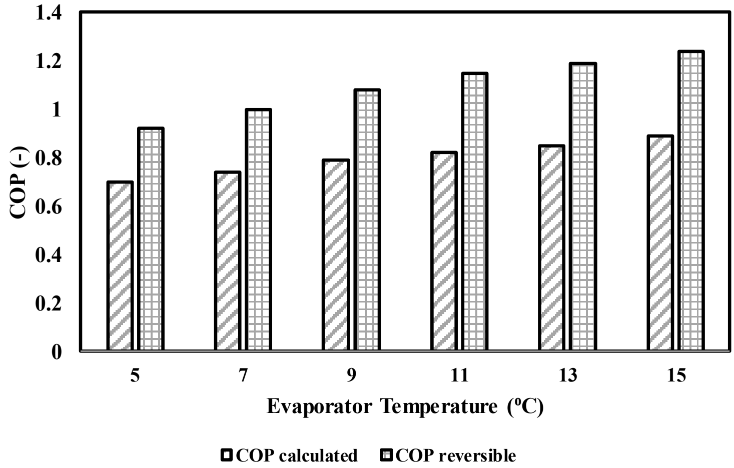

Figure 3. Variation in COP with evaporator temperature

4.2 Impact of Evaporator Temperature Variation on COP:

A rise in evaporator temperature from 5°C to 15°C causes COP to improve linearly as shown in figure 3, with a rise of approximately 25%. This is due to the increased evaporator temperature reducing the pressure difference throughout the system and the required circulation work. It also increases the vapor pressure of the refrigerant, hence enhancing the absorption process. But too much increase in evaporator temperature can decrease the cooling effect and limit its utility. Therefore, keeping evaporator temperatures near the desired cooling level ensures high system efficiency.

4.3 Effect of Variation in Condenser Temperature on COP:

With a rise in condenser temperature from 30°C to 50°C, reversible COP falls considerably by 35%, whereas theoretical COP falls slightly by 10% as depicted in figure 4. Condenser temperatures higher than this require additional energy for condensation, increasing the heat load of the generator and decreasing overall efficiency. Furthermore, high condenser temperature elevates condensing pressure, which becomes detrimental to refrigerant flow. Thus, it is essential to keep the condenser temperature low through efficient cooling systems.

4.4 Effect of Variation in Absorber Temperature on COP:

Raising absorber temperature from 23°C to 43°C decreases COP by almost 30% in theoretical terms, whereas reversible COP is close to being unchanged as shown in figure 5. The reason is that increased absorber temperature decreases the absorption capacity of the solution, so strong solution circulation will be required in greater amounts to keep it performing. This is associated with increased energy input and pump work and, therefore, decreased net efficiency. Keeping the absorber close to ambient temperature is therefore of prime importance for maximizing absorption.

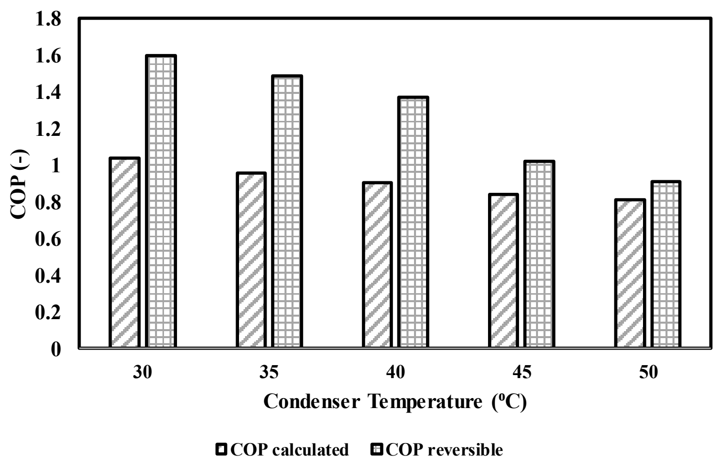

Figure 4. Variation in COP with condenser temperature

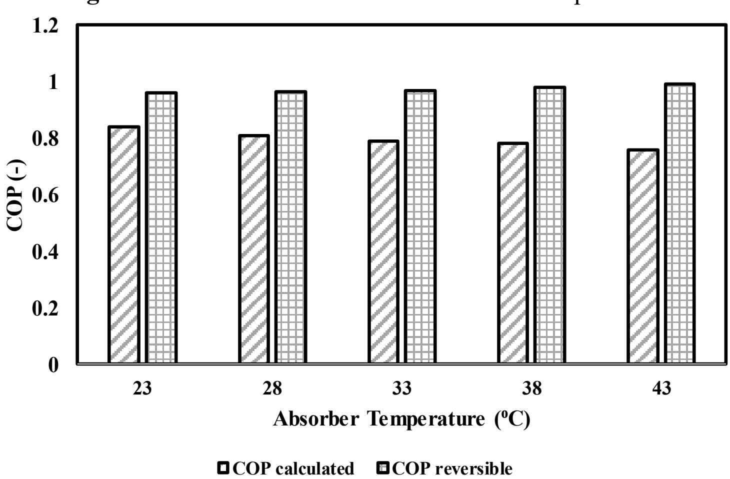

Figure 5 Variation in COP with absorber temperature

4.5 Impact of Variation in Effectiveness of Solution Heat Exchanger on COP:

Enhancing the effectiveness of the solution heat exchanger from 0.6 to 0.85 makes the COP improve by approximately 15% as shown in figure 6. This is because the high-effectiveness exchangers improve the pre-heating of the concentrated solution, thereby lowering the generator thermal load. Since less external heat is needed to achieve the boiling point, system efficiency improves. Such exchangers with high effectiveness therefore play a major role in system optimization with a relatively low mechanical complexity.

4.6 Impact of Temperature Fluctuations on Pump Work:

Variation in pump work with change in absorber, generator, condenser, and evaporator temperature is exhibited in figure 7. Pump work is at variance with temperature variation. Pump work rises by 12% with increased absorber temperature because of decreased solution density and inefficient absorption. A generator temperature increase first decreases pump work by 10% but tapers off after 95°C. An elevated condenser temperature increases pump work by 8% by increasing pressure difference, whereas a rise in evaporator temperature decreases pump work by 15% because of improved pressure balance. Therefore, reducing the absorber and condenser temperatures and optimizing generator and evaporator conditions results in reduced auxiliary energy input.

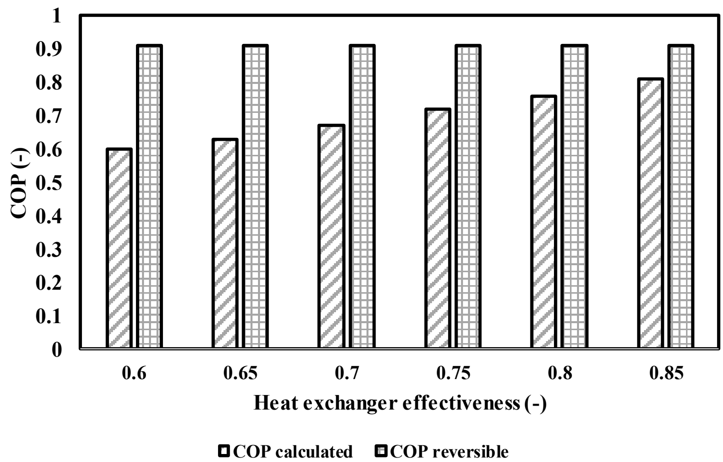

Figure 6. Variation in COP with heat exchanger effectiveness

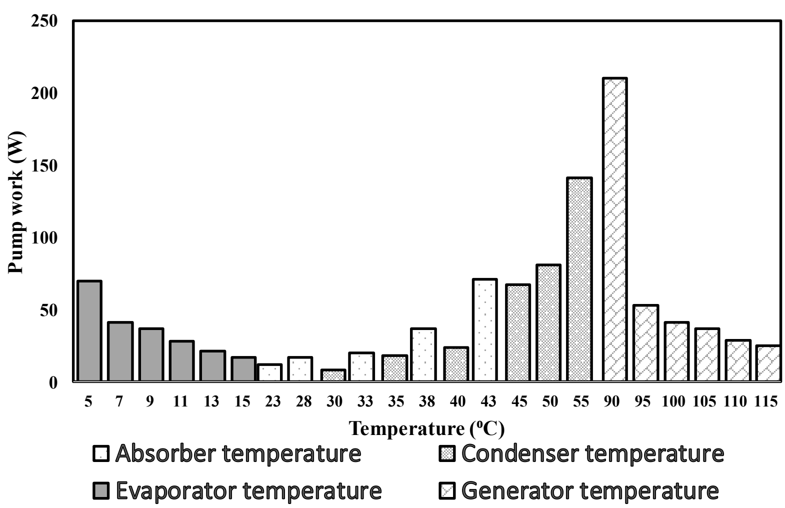

Figure 7. Variation in Pump work with different temperatures

Based on the theoretical results of this research, subsequent work will consist in the fabrication and experimental verification of the proposed VARS to determine real-time performance, particularly under hot climatic conditions and high traffic conditions where exhaust heat is always present. The versatility of the system across various engine sizes and vehicle types, like delivery scooters or e-rickshaws, offers a thrilling prospect, though there are challenges like spatial integration, fluctuating heat availability, and component scaling that need to be overcome. Opportunities also exist to create hybrid systems by integrating VARS with traditional vapour compression systems for increasing cooling responsiveness and dependability at low-load operation. Additionally, environmental safety in terms of usage, leakage, and disposal of LiBr will be deeply analyzed during the prototype development. Overall, this idea opens the door to sustainable, scalable, and application-specific cooling solutions for the personal mobility industry.

5 Conclusion

This paper proposes a conceptual configuration and thermodynamic evaluation of a lithium bromide–water (LiBr–H_2O) vapour absorption refrigeration system (VARS) designed for two-wheelers, using waste engine exhaust gas heat. The system is shown to have an actual COP of 0.7365 and theoretical limiting COP of 0.944 under practical conditions. The cooling is provided by a wearable jacket-type evaporator, and it presents a bespoke thermal comfort solution. Although the research is theoretical, it sets the possibility of utilizing low-grade thermal energy for sustainable, rider-oriented cooling without supplementary mechanical or electrical power inputs. Energy autonomy is enhanced further by including a thermoelectric generator (TEG). Environmental needs have also been considered by considering LiBr as working substance due to it's non-toxic, non-flammable, and ozone-friendly characteristics. While no physical prototype has been developed at this stage, the analysis exhibits a solid basis for subsequent development, experimental validation, and real-world deployment across several vehicle platforms and climatic conditions.

References

1. Alomary MQ, Hammadi SH. Lithium Bromide-Water Absorption Refrigeration System Driven by Automobile Exhaust Gas: Thermodynamic Study. Journal of Advanced Research in Experimental Fluid Mechanics and Heat Transfer. 2025 May 29;20(1):102-20.
2. Alshammari NK. An examination of the exergy and energy of a solar powered absorption cooling systems in the Riyadh climate. Journal of Engineering Research. 2025 Mar 19.
3. Aly WI, Abdo M, Bedair G, Hassaneen AE. Thermal performance of a diffusion absorption refrigeration system driven by waste heat from diesel engine exhaust gases. Applied Thermal Engineering. 2017 Mar 5;114:621-30.
4. Mohammadi K, Khaledi MS, Powell K. A novel hybrid dual-temperature absorption refrigeration system: Thermodynamic, economic, and environmental analysis. Journal of cleaner production. 2019 Oct 1;233:1075-87.
5. Ali FH, Al-Amir QR, Hamzah HK, Alahmer A. Unveiling the potential of solar cooling technologies for sustainable energy and environmental solutions. Energy Conversion and Management. 2024 Dec 1;321:119034.
6. Patil B, Salunke N, Diware V, Raheman AR S, Ansari KB. Stability assessment of emerging phase change materials for solar thermal storage in absorption refrigeration: A review. International Journal of Green Energy. 2025 Jan 25;22(2):253-80.

7. Jassim L, Mnati HM, Abd Ali FA, Majdi HS. Photovoltaic-Driven Cooling Systems: Advances, Challenges, and Future Directions. Al-Rafidain Journal of Engineering Sciences. 2025 Jan 23:191-209.
8. ElBahloul AA, Zeidan ES, El-Sharkawy II, Hamed AM, Radwan A. Experimental and numerical investigation of multistage sorption energy storage system. Applied Thermal Engineering. 2023 Jan 5;218:119313.
9. Ajay A, Gill RS, Singh RP. Performance Evaluation of LiBr-H_2O Vapours Absorption System for an Office Building Cooling. Adv. Res. 2020 Jun. 24;21(7):9-21.
10. Alfaris A, Akroot A, Alqaed S, Almehmadi FA. Performance analysis of integrated solar and natural gas combined cycle power plants in high solar potential regions. Scientific Reports. 2025 Mar 17;15(1):9181.
11. Singh DV, Verma TN. Energy and exergy analysis of LiBr-H_2O-operated vapour absorption refrigeration system using the ANN approach. International Journal of Ambient Energy. 2022 Dec 31;43(1):905-17.
12. Zhou T, Liu J, Ren J, Yang S. Comprehensive assessment of a coupled LiBr/H_2O absorption refrigeration/ORC system for low-grade residual heat recovery based on advanced exergy and exergo-economic analysis. ACS Sustainable Chemistry & Engineering. 2022 Apr 27;10(18):5825-37.
13. Yadav JS, Rao CM, Kumar VV. Performance of Vapour Absorption Refrigeration System using Waste Heat Source. i-Manager's Journal on Mechanical Engineering. 2020 May 1;10(3):45.
14. Dubey A, Arora A. Solar-Driven Vapour Absorption (LiBr–H2O) Cooling Systems for Commercial Buildings: A Parametric Analysis. InInternational Conference on Recent Advancements in Mechanical Engineering 2020 Jul 8 (pp. 187-198). Singapore: Springer Nature Singapore.
15. Staudt S, Unterberger V, Gölles M, Wernhart M, Rieberer R, Horn M. Control-oriented modeling of a LiBr/H_2O absorption heat pumping device and experimental validation. Journal of Process Control. 2023 Aug 1;128:103024.