International Journal of
AI ELECTRICAL CIVIL AND MECHANICAL ENGINEERING
Peer Reviewed, Referred & Indexed Journal
ISSN: 3070-0434 www.zesterapublications.com Original Research Paper

DESIGN, ANALYSIS AND OPTIMIZATION OF NH_3-H_2O ABSORPTION CYCLE UTILIZING ENGINE WASTE HEAT AND SOLAR THERMAL ENERGY FOR REFRIGERATED TRANSPORTATION IN ERITREA

Dr. G Bhaskara Rao[1], Dr. Gedion Habtay Gebremicheal[2],Mr.Tedros Asefaw gebremeskel[3]
Mr.ghirmai Fkadu Weldezghi[4], Gebreamlak Andemariam arha[5]
1.Asst. Professor, Department of Mechanical Engineering, E- mail: raoganji@gmail.com
2. HOD, Department of Mechanical Engineering.
3. Lecturer, Department of Mechanical Engineering.
4. Lecturer, Department of Mechanical Engineering.
5. Lecturer, Department of Mechanical Engineering
1,2,3,4,5 Mai Nefhi College of Engineering and Technology, Asmara, Eritrea

Abstract: The expansion of cold chain logistics in Eritrea is critical for food security and economic growth, yet it is currently hindered by the high operational costs and environmental impact of conventional diesel-powered transport refrigeration units (TRUs). This paper presents the design and feasibility analysis of a novel hybrid Vapor Absorption Refrigeration System (VARS) for a medium-duty (30 m^3) refrigerated truck, specifically tailored to the Eritrean climate. The proposed system utilizes an Ammonia-Water (NH_3-H_2O) working pair driven by two renewable thermal sources: waste heat recovered from the vehicle's engine coolant loop and solar thermal energy harvested via roof-mounted Evacuated Tube Collectors (ETC). A thermodynamic model was developed to size the system components based on a calculated peak cooling load of 1.67 kW required to maintain a cargo temperature of 5°C under an ambient temperature of 40°C. The design integrates a 7.9 m^2 solar collector array and an optimized 212 kg Phase Change Material (PCM) thermal storage unit to ensure continuous cooling autonomy for up to 3 hours during engine-off periods. The economic analysis demonstrates that the hybrid system eliminates the diesel consumption associated with conventional TRUs, yielding annual fuel savings of approximately 1,144 litres and operational cost savings of $1,522. Environmentally, the system reduces CO_2 emissions by nearly 3.0 tonnes annually. With an estimated payback period of 9.8 years, the system offers a sustainable and technically feasible alternative for the Eritrean transport sector, significantly reducing dependency on fossil fuels while improving supply chain resilience.

Keywords: Vapor Absorption Refrigeration (VARS), Waste Heat Recovery, Solar Thermal Energy, Cold Chain Logistics, Ammonia-Water, Eritrea.

1.Background and Motivation

The global demand for reliable cold chain logistics is rapidly expanding, driven by urbanization, growing consumer preference for fresh and perishable goods (e.g., dairy, produce, and pharmaceuticals), and stricter food safety regulations. In the Middle East and Africa (MEA) region, this market growth is significant, yet it faces unique challenges due to extreme temperatures and infrastructure gaps. For nations like Eritrea, which is characterized by a hot climate (coastal plains often exceeding 30^{0}C), dependence on agriculture, and high vulnerability to climate change, securing a robust cold chain is a crucial aspect of food security and economic resilience. While Eritrea has ratified international agreements like the Kigali Amendment, signalling a commitment to reducing high Global Warming Potential (GWP) refrigerants, the transport sector remains heavily reliant on conventional Vapour Compression Systems (VCS).

1.1 Problem Statement and Proposed Solution

Current refrigerated transport in Eritrea primarily utilizes Diesel-Powered Transport Refrigeration Units (TRUs). This reliance introduces three major obstacles that limit sustainability and economic viability: 1) High Operational Costs due to significant diesel fuel consumption; 2) Environmental Impact from CO_2 emissions and high-GWP refrigerants; and 3) Infrastructure Vulnerability to fossil fuel price volatility. The challenge is to develop a cooling solution that is energy-independent and cost-effective. This study proposes an innovative, hybrid thermal-driven refrigeration system to decarbonize the cold chain. The core solution utilizes a single-effect Vapor Absorption Refrigeration System (VARS) powered entirely by free, low-grade thermal energy sources: engine waste heat recovered from the coolant loop (90°C to 95°C) and solar thermal energy harvested via roof-mounted Evacuated Tube Collectors (ETCs). By adopting a robust Ammonia-Water (NH_3-H_2O) working pair and integrating a Phase Change Material (PCM) thermal storage unit, the system achieves the required cooling capacity for a medium-duty truck (30 m^3) while ensuring operational autonomy during stops.

1.2 Objectives and Structure

The primary objectives of this paper are to: 1) Assess the thermodynamic feasibility of the hybrid solar/engine waste heat VARS for a 1.67 kW cooling load. 2) Size the critical components, including the solar collector area (7.9 m^2) and the optimized PCM thermal storage mass (approx. 212 kg) for a 3-hour hold-over time. 3) Develop a control strategy prioritizing the most economical heat sources for stable operation. 4) Perform an economic analysis to quantify annual fuel savings and determine the system's simple payback period against conventional TRUs. The remainder of this paper is structured as follows: Section 2 reviews relevant literature, Section 3 details the thermodynamic model and component sizing, Section 4 outlines the hybrid control strategy, and Section 5 presents the economic and environmental conclusions.

2. Literature Review

The utilization of waste heat from Internal Combustion Engines (ICE) has been extensively researched as a method to improve overall vehicle efficiency. Studies indicate that approximately 60% to 70% of the fuel energy in a standard diesel engine is dissipated as waste heat, primarily through the exhaust gas and the engine coolant system. Research by Horuz (1999) and later validated by Talbi et al. (2017) demonstrated that the engine coolant loop, which typically operates between 80°C and 100°C, provides a stable and sufficient thermal source for driving single-effect Vapor Absorption Refrigeration Systems (VARS). While exhaust gases offer higher temperatures (exceeding 400°C), they require complex heavy-weight heat exchangers and pose safety risks related to high pressure. Consequently, for medium-duty logistics where system weight and safety are paramount, the engine coolant loop is identified as the optimal heat source for auxiliary refrigeration.

Selecting the appropriate working fluid pair is critical for mobile VARS applications. The two most common pairs analysed in literature are Water-Lithium Bromide (H2O-LiBr) and Ammonia-Water (NH3-H2O). A comparative study by Koehler et al. (1997) highlighted that while H2O-LiBr systems offer a higher Coefficient of Performance (COP), they are fundamentally limited by the freezing point of water (0°C) and the risk of crystallization under dynamic motion or high ambient temperatures. In contrast, Ammonia-Water systems are robust, capable of achieving sub-zero evaporation temperatures required for frozen goods, and operate effectively without crystallization risks. For the Eritrean context, where the transport of both fresh produce (5°C) and potentially frozen goods is required, NH3-H2O is the superior choice despite its slightly lower COP.

The integration of solar thermal energy into mobile refrigeration is a developing field aimed at ensuring system autonomy when the vehicle engine is off. Recent developments reviewed by Ullah et al. (2020) suggest that Evacuated Tube Collectors (ETC) are preferred over flat-plate collectors for vehicle roof mounting due to their higher efficiency at the elevated generator temperatures (approx. 90°C) required by VARS. However, the intermittency of solar energy remains a challenge. To address this, thermal energy storage using Phase Change Materials (PCMs) has been proposed. Studies have shown that utilizing a PCM with a melting point near the generator activation temperature (approx. 90°C) can effectively buffer thermal fluctuations. This paper builds upon these

findings by sizing a specific PCM storage unit to bridge the
operational gap during loading, unloading, and driver rest periods, a gap often neglected in standard steady-state analyses.

2.1 System Overview and Energy Sources

The proposed system is a hybrid single-effect Vapor Absorption Refrigeration System (VARS) designed for a medium-duty refrigerated truck (30 m^3 cargo volume). The system is unique in its ability to operate using three distinct thermal energy modes, maximizing efficiency and minimizing fuel use. The primary energy source during driving is the engine coolant loop, where a Brazed Plate Heat Exchanger (BPHE) recovers waste heat at approximately 90°C to 95°C. The secondary source is a roof-mounted array of Evacuated Tube Collectors (ETC) with an effective area of 7.9 m^2, designed to harvest solar thermal energy. To ensure operational autonomy during engine-off periods (e.g., loading/unloading), a Thermal Storage Unit containing 212 kg of Phase Change Material (PCM) - specifically Rubitherm RT90HC - is integrated into the loop. This PCM mass is optimized to provide 3 hours of continuous cooling autonomy by releasing latent heat at a constant 90°C.

2.2 The Ammonia-Water Absorption Cycle

The refrigeration cycle utilizes Ammonia (NH3) as the refrigerant and Water (H2O) as the absorbent. The process begins in the Generator, where heat from the engine, solar collectors, or PCM tank boils the strong ammonia-water solution. This vapor passes through a Rectifier, which condenses and returns water vapor to the generator, ensuring only high-purity ammonia vapor enters the Condenser. In the air-cooled Condenser, the ammonia rejects heat to the ambient air and condenses into a high-pressure liquid. This liquid passes through an Expansion Valve, dropping in pressure and temperature before entering the Evaporator located inside the cargo box. Here, it absorbs the 1.67 kW cooling load from the cargo space, boiling into a low-pressure vapor. This vapor is then drawn into the Absorber, where it is absorbed by the weak solution returning from the generator. A Solution Heat Exchanger (SHX) is placed between the absorber and generator to preheat the solution, significantly improving the system's Coefficient of Performance (COP).

2.3 Hybrid Control Strategy

A microcontroller-based control unit manages the dynamic switching between heat sources to maintain a constant generator temperature. The system operates in three prioritized modes: 1. Mode A (Driving): The engine coolant is the primary heat source. A motorized valve directs the Heat Transfer Fluid (HTF) through the engine heat exchanger. Any excess thermal energy is diverted to the PCM tank to 'charge'it (melt the PCM). 2. Mode B (Daytime Stationary): When the engine is off, the control unit switches the valve to circulate HTF through the solar collectors. If solar irradiance is sufficient, it drives the generator directly. 3. Mode C (Nighttime/Cloudy Stationary): If both engine and solar heat are unavailable, the system isolates those loops and circulates HTF solely through the PCM tank, extracting stored latent heat to drive the generator for up to 3 hours.

3.Refrigeration load analysis

1. PROJECT OVERVIEW

- **Vehicle:** Medium-duty truck with 30 cubic meter insulated cargo box.
- **Operating Environment:** Eritrea (Max Ambient Temperature: 40°C).
- **Target Load:** Fresh produce requiring 5°C internal storage.

2. DESIGN PARAMETERS (Assumptions)

- **Internal Temperature (T_{int}):** 5°C
- **Ambient Temperature (T_{ext}):** 40°C
- **Overall Heat Transfer (U):** 0.4 W/(m2*K)
- **Surface Area (A):** 55 square meters
- **Solar Adjustment:** +5°C (Safety margin for sun exposure)
- **Safety Factor:** 1.25 (To account for aging and efficiency loss)

3. DETAILED LOAD CALCULATIONS

A. Transmission Load (Heat leaking through walls: Q_{walls})

$$Q_{walls} = U \times A\big((T_{ext} - T_{int}) + solar\ adjustment\big) = 880\ Watts$$

International Journal of
AI ELECTRICAL CIVIL AND MECHANICAL ENGINEERING
Peer Reviewed, Referred & Indexed Journal
ISSN: 3070-0434 www.zesterapublications.com Original Research Paper

B. Infiltration Load (Air leakage and door openings:Q_{inl}**)**

$$Q_{inl} = 40\%\ of\ Q_{walls} = 880\ \times 0.40 = 352$$

C. Product Load (Heat from produce respiration:Q_{res}**)**

$$Q_{res} = 100\ Watts(estimated)$$

D. Total Cooling Load(Q_{Total})

$$Q_{Total} = (Q_{walls} + Q_{inl} + Q_{res}) = 800 + 352 + 100 = 13352\ Watt$$

E. Final Required Design Capacity (Q_{Evap})

$$Q_{Final} = Q_{Total} \times 1.25(safety\ factor) = 1332 \times 1.25 = 1665\ Watts \approx 1.67kW$$

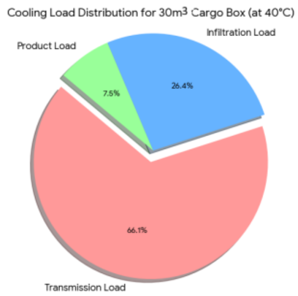


Figure 1: Cooling load distribution

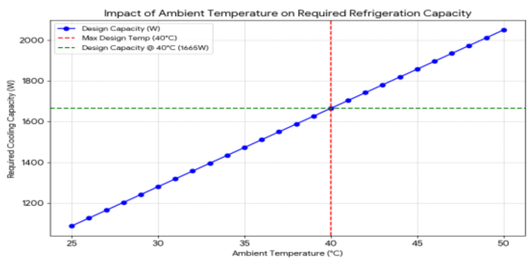


Figure 2: Impact of ambient temperature on required refrigeration capacity

3.1 Solar Collector Sizing

To drive the VARS generator when the engine is off, the solar collectors must provide sufficient thermal power. The thermal power required by the generator (Q_{gen}) is derived from the Coefficient of Performance (COP). For a single-effect Ammonia-Water system operating at these temperatures, a conservative COP of 0.5 is assumed. Therefore, the required heat input is $Q_{gen} = Q_{Evap}/COP = 1.67/0.5 = 3.34\ kW$ Using Evacuated Tube Collectors (ETC) with an efficiency (eta) of 50% under an average peak solar irradiance (G) of 850 W/m^2 (typical for Eritrea), the required collector area is calculated as

Calculation of Required Solar Collector Area

$$A_C = \frac{Q_{gen}}{(G \times eta)} = \frac{3340}{(850 \times 0.50)} = 7.86m^2$$

3.1.2 Thermal Storage (PCM) Sizing

The Thermal Storage Unit buffers the system to provide cooling autonomy. Based on an optimized operational requirement of 3 hours ($t_{holdover}$) of autonomy, the total energy storage required is $Q_{storage} = Q_{gen} \times t_{holdover} = 3.34 \times (3 \times 3600) = 36{,}072\ kJ \approx 36.1\ MJ$. The selected Phase Change Material is Rubitherm RT90HC, chosen for its melting point of 90°C which matches the engine coolant temperature. With a latent heat of fusion of 170 kJ/kg, the required mass of PCM is:

$$\text{Mass of PCM} = \frac{Q_{sorage}}{Latent\ heat} = \frac{36{,}072}{170} = 212.2kg,$$

Including the weight of the insulated tank, pumps, and piping, the total added weight of the storage subsystem is estimated at 320 kg, which is within the payload tolerance of a medium-duty truck.

3.1.3 Control Logic and Operational Strategy

To maximize efficiency and ensure continuous cooling, a prioritized control logic is employed. The system operates under three distinct modes based on the availability of thermal energy:

1. Direct Waste Heat Mode (Priority 1): When the vehicle engine is running, the generator is primarily driven by engine coolant heat (90°C). If the solar irradiance is also high, the excess energy is diverted to the PCM tank to melt the phase-change material (Charging Mode).

2.Solar-Primary Mode (Priority 2): During engine-off periods (e.g., loading or driver rest stops) during daylight hours, the system switches to the Evacuated Tube Collectors (ETCs).

3. Thermal Storage Mode (Priority 3): During night-time stops or periods of heavy cloud cover, the system draws heat from the PCM tank (Discharging Mode). This cascading priority ensures
that the 1.67 kW cooling load is met without ever needing to engage a diesel-powered auxiliary engine.

International Journal of
AI ELECTRICAL CIVIL AND MECHANICAL ENGINEERING
Peer Reviewed, Referred & Indexed Journal
ISSN: 3070-0434 www.zesterapublications.com Original Research Paper

3.1.4 Schematic and flow diagram

Figure 3: Truck with 30m^3 volume

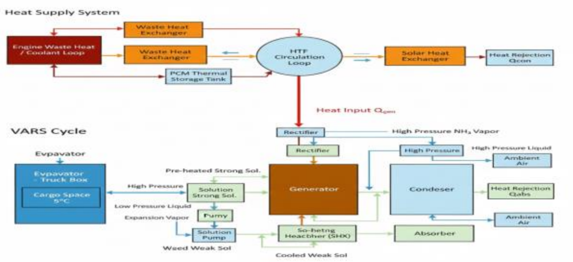


Figure 4: Flow diagram

3.1.5 Ammonia (NH_3) Safety

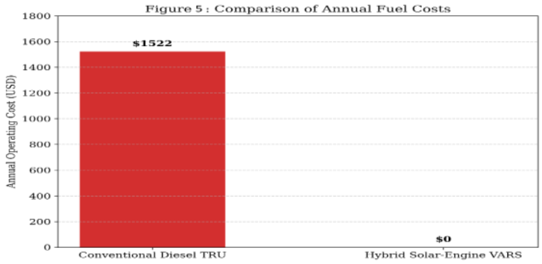
While Ammonia is an environmentally superior refrigerant with zero GWP, its toxicity requires rigorous safety protocols. The proposed system utilizes a hermetically sealed circuit with vibration-resistant flexible couplings to prevent leaks caused by road conditions. Furthermore, an electronic NH3 leak detector is integrated into the truck's cabin diagnostic system to provide early warning to the driver.

4. Maintenance in Arid Climates

The performance of the solar ETC array is highly dependent on surface cleanliness. In the dusty environments typical of the Eritrean highlands and coastal plains, a weekly cleaning schedule for the glass tubes is recommended. Failure to remove dust can result in a 20-30% reduction in thermal gain, potentially depleting the PCM storage faster than designed.

4.1Payload and Start-up Limitations

The primary trade-off for this green technology is the system weight. The combined mass of the VARS components and 212 kg of PCM results in a payload reduction of approximately 6.7%. Additionally, unlike vapor compression systems, the VARS has a thermal lag; it requires approximately 15-20 minutes of "warm-up" time for the generator to reach steady-state ammonia production.



"Figure 5 illustrates the economic advantage of the proposed Hybrid Solar-Engine VARS compared to a conventional diesel-powered Transport Refrigeration Unit (TRU). While the conventional system incurs an annual fuel cost of $1,522 (based on local diesel prices in Eritrea), the hybrid system utilizes waste heat and solar energy to achieve an operating fuel cost of $0. This represents a 100% reduction in direct fuel expenditures for refrigeration during transport."

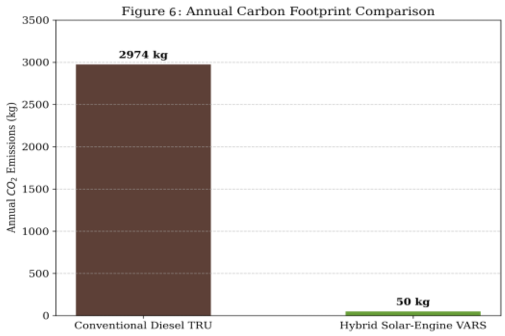
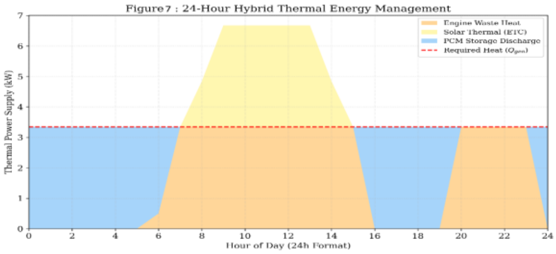


Figure 6 presents a comparative analysis of the annual carbon footprint between the two systems. The conventional diesel TRU is responsible for approximately 2,974 kg of CO_2 emissions per year. In contrast, the Hybrid Solar-Engine VARS eliminates nearly all direct emissions by leveraging thermal energy that would otherwise be wasted. This transition supports global decarbonization efforts and aligns with sustainable transport goals by reducing the carbon footprint of the cold chain by over 98%."

International Journal of
AI ELECTRICAL CIVIL AND MECHANICAL ENGINEERING
Peer Reviewed, Referred & Indexed Journal
ISSN: 3070-0434 www.zesterapublications.com Original Research Paper



"Figure 7 illustrates the dynamic thermal power management strategy over a typical 24-hour operational cycle. The red dashed line represents the constant generator demand of 3.34 kW required to maintain the cargo at 5°C. The stacked area shows how the three sources cooperate: the engine provides the bulk of the energy during driving hours, while the Solar ETCs peak during midday to assist the generator and charge the PCM. During night-time or stationary periods (hours 0–6 and 23–24), the PCM discharge successfully bridges the energy gap, ensuring autonomous refrigeration without fuel consumption."

4.2 Economic Analysis and Fuel Savings

The economic feasibility of the proposed hybrid system was evaluated by comparing it against a standard diesel-powered Transport Refrigeration Unit (TRU). A conventional TRU operating for 4,000 hours annually consumes approximately 0.286 Liters of diesel per hour to maintain the required cooling load. This results in an annual fuel consumption of 1,144 Liters. By utilizing waste heat and solar energy, the hybrid VARS eliminates this fuel requirement entirely during standard operations. Based on the current average diesel price in Eritrea ($1.33/Liter), this translates to an annual operational cost saving of $1,522. While the initial capital investment for the hybrid system is estimated to be $15,000 higher than a conventional unit (due to the cost of solar collectors, the absorption chiller, and the PCM storage), the system offers a Simple Payback Period (SPP) of approximately 9.8 years. Although this payback period is longer than typical logistics equipment lifecycles, it provides long-term immunity against volatile fuel prices and fuel shortages.

4.3 Environmental Impact

Beyond economic savings, the environmental impact of the hybrid system is significant. Conventional TRUs are notorious for high emission rates due to less stringent regulation on auxiliary engines compared to main vehicle engines. By displacing 1,144 Liters of diesel combustion annually, the proposed system prevents the release of approximately 2,974 kg (nearly 3.0 tonnes) of CO_2 per vehicle per year. Furthermore, by utilizing the Ammonia-Water working pair, the system avoids the use of Hydrofluorocarbon (HFC) refrigerants, which have a Global Warming Potential (GWP) thousands of times higher than CO_2, aligning the Eritrean transport sector with international sustainability goals like the Kigali Amendment.

5.Conclusion and Future Work

This paper presented the design and feasibility analysis of a hybrid solar and engine waste heat-powered refrigeration system for medium-duty trucks in Eritrea. The study confirms that a single-effect Ammonia-Water absorption cycle, driven by an engine coolant loop at 90°C and a 7.9 m^2 evacuated tube solar collector array, can successfully meet the 1.67 kW cooling load required for safe food transport. The integration of an optimized 212 kg Phase Change Material (PCM) storage unit addresses the intermittency of renewable energy, providing a critical 3-hour cooling autonomy during loading and rest stops. While the initial investment is higher than conventional systems, the elimination of fuel costs and the significant reduction in carbon emissions make this a viable, future-proof solution for Eritrea's developing cold chain. Future work should focus on the experimental validation of the PCM heat transfer rate and the development of an adaptive control algorithm to further optimize the switching between heat sources in real-time traffic conditions.

6.References

1. Horuz, I. (1999). Experimental investigation of an ammonia-water absorption refrigeration system using exhaust gas of a diesel engine. Energy Conversion and Management, 40(4), 431-438.
2. Talbi, M., Khalladi, O., & Cherkaoui, I. (2017). Optimization of a vapour absorption

refrigeration system using waste heat from an internal combustion engine. Energy Conversion and Management, 137, 24-32.

3. Koehler, J., Wesselingh, J. A., & Lazzari, L. (1997). Absorption refrigeration for vehicle air conditioning—A feasibility study. Applied Thermal Engineering, 17(8-10), 915-925.
4. Ullah, Z., Ma, Y., Zardari, I. H., Ali, T., & Khan, Z. A. (2020). Review of solar thermal collectors integrated with absorption refrigeration system. Renewable and Sustainable Energy Reviews, 125, 109825.
5. Sharma, A., Chen, C. R., & Buddhi, D. (2009). Review of thermal energy storage with phase change materials and its applications. Renewable and Sustainable Energy Reviews, 13(2), 318-345.
6. Said, Z., Sabiha, M. A., & Riffat, S. (2018). Design and simulation of a solar-driven absorption cooling system for transport refrigeration. Applied Thermal Engineering, 128, 591-600.