International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347 - 6435 (Online)) Volume 14, Issue 3, March 2025)

Econometric and Thermodynamic Evaluation of Renewable-Assisted Hybrid Refrigeration Systems: A Comparative Study of VCRS and CVCAS Using Solar, Geothermal, and Industrial Waste Heat

Shubham Kanungo[1], Ashwini Joshi[2],

[1]Assistant Professor, IPS Academy, Institute of Engineering & Science, Indore
[2]Associate Professor, IPS Academy, Institute of Engineering & Science, Indore

Abstract— **The Refrigeration systems are pivotal in sectors such as healthcare, food preservation, and pharmaceuticals. However, conventional vapor compression systems (VCRS) are highly energy-intensive and contribute significantly to greenhouse gas emissions. This paper expands on the comparative analysis between VCRS and a Cascaded Vapor Compression-Absorption System (CVCAS) by incorporating the impact of integrating renewable and low-grade energy sources like solar thermal, geothermal, and industrial waste heat for absorption system operation. The integration enhances sustainability, reduces carbon footprints, and improves long-term economic viability. A detailed thermodynamic, economic, and environmental performance assessment is presented, demonstrating that renewable-assisted CVCAS significantly lowers operating costs and emissions while maintaining cooling performance. Furthermore, the study evaluates policy implications, recommending that institutional support and green energy subsidies can accelerate the adoption of hybrid refrigeration systems. This aligns with the theme of shaping future-ready economic systems through people-centered, policy-driven innovation.**

Keywords—**Ayurvedic CVCAS, Solar Thermal, Geothermal, Industrial Waste Heat, Sustainability, Refrigeration, Econometric Analysis, Green Economy, Policy Innovation.**

I. .INTRODUCTION

This document is Refrigeration plays a vital role in industrial, commercial, and healthcare sectors, ensuring product preservation, thermal comfort, and process stability. Conventional Vapor Compression Refrigeration Systems (VCRS), though widely used, are highly energy-intensive and primarily dependent on electricity, leading to increased operational costs and environmental impact due to greenhouse gas emissions. As a sustainable alternative, hybrid systems such as Cascaded Vapor Compression–Absorption Systems (CVCAS) have emerged, offering improved energy efficiency by integrating renewable heat sources like solar, geothermal, and industrial waste heat.

The combination of compression and absorption cycles allows for effective load sharing and reduced reliance on high-grade electrical energy. Studies have shown that integrating geothermal energy into a compression-absorption system enhances cooling performance while reducing energy consumption [1]. Similarly, hybrid systems employing lithium bromide-water or ammonia-based working fluids have demonstrated significant thermodynamic advantages in terms of coefficient of performance (COP) and exergetic efficiency [3], [5], [6].

Economically, hybrid systems have shown promising potential. [2] conducted a performance and economic analysis of combined absorption/compression heat pumps, indicating a substantial reduction in operating cost compared to standalone compression systems. Moreover, the hybrid approach facilitates simultaneous cooling and heating, making it viable for cogeneration applications [4].

II. System Descriptions

Vapor Compression Refrigeration Systems (VCRS) function through a cyclic thermodynamic process involving four key stages: compression, condensation, expansion, and evaporation. In this cycle, a refrigerant absorbs heat from the low-temperature space during evaporation and releases it to a higher temperature sink during condensation, facilitated by an electrically driven mechanical compressor.

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While VCR systems are well-established and offer high cooling efficiency, they are heavily dependent on electrical energy and often utilize synthetic refrigerants with high global warming potential. To address these environmental and energy challenges, alternative systems and hybrid cycles are being investigated. Hulten and Berntsson [6] demonstrated that modifying system parameters in compression/absorption cycles can significantly enhance the coefficient of performance (COP), making them viable alternatives to pure VCR systems. Similarly, Sun [9] compared various absorption systems and concluded that environmentally benign working pairs like NH_3-H_2O and NH_3-$LiNO_3$ offer promising pathways toward sustainable refrigeration

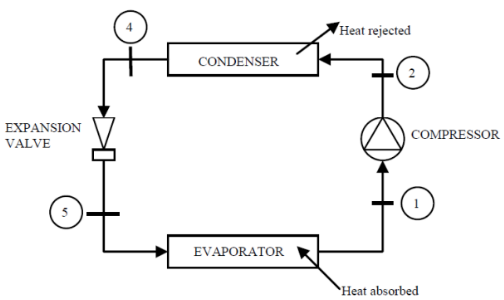

Figure 1. Vapor Compression Cycle Developed as per Stoecker and Jones, 1982.

Cascaded Vapor Compression-Absorption System (CVCAS) CVCAS integrates a VCRS with a Vapor Absorption Refrigeration System (VARS), connected via a cascade heat exchanger. The VARS section is powered by thermal energy instead of electricity, reducing compressor load. This study evaluates performance when VARS is driven by:

- Solar thermal energy
- Geothermal heat
- Industrial waste heat

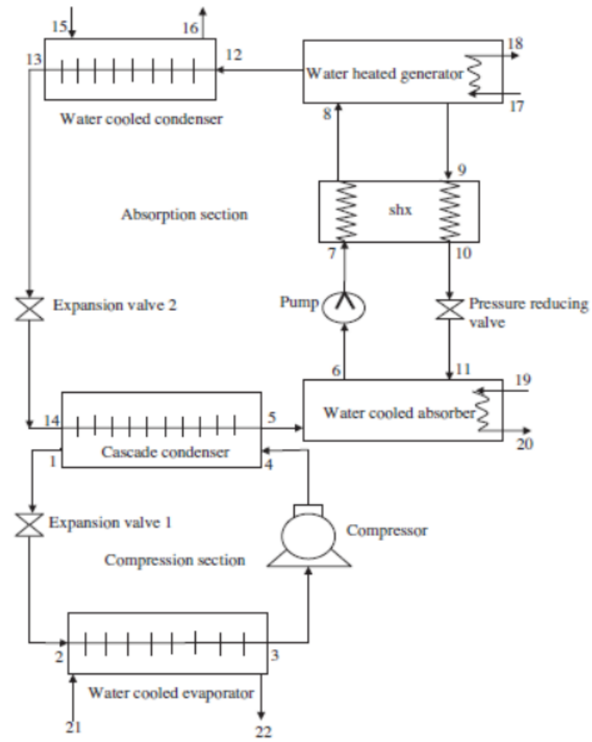

Figure 2: Vapor Compression Vapor Absorption Cascaded System

III. Impact of Renewable Heat Sources

3.1 Solar Thermal Integration Solar collectors (flat plate or evacuated tube) supply heat to the absorber generator pair. The intermittency of solar input necessitates thermal storage but offers zero-emission energy.

3.2 Geothermal Integration Shallow or deep geothermal reservoirs provide continuous low-grade heat (~60°C to 120°C). This ensures 24/7 VARS operation, improving system reliability.

3.3 Industrial Waste Heat Many industries release low-grade heat as a byproduct (e.g., from exhausts or steam condensate). Utilizing this waste heat reduces fuel consumption and enhances overall energy efficiency.

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IV. Economic Analysis

Parameter	VCRS	CVCAS (Base)	CVCAS + Solar	CVCAS + Geothermal	CVCAS + Waste Heat
Capital Cost (INR)	300,000	1,500,000	1,800,000	1,600,000	1,550,000
Daily Electricity Cost (INR)	1,805	870	720	690	710
Annual Electricity Cost (INR)	649,800	313,200	262,800	251,850	258,150
Net Annual Savings (INR)	–	336,600	387,000	397,950	391,650
Payback Period (years)	–	5.0	4.7	4.3	4.2
Breakeven Point (years)	–	3.2	3.0	2.6	2.7

V. Environmental Impact

Source	CO_2 Reduction (%)	Electricity Reduction (%)
CVCAS (Base)	55–60%	50–55%
CVCAS + Solar	65–70%	58–62%
CVCAS + Geothermal	68–73%	60–65%
CVCAS + Waste Heat	66–70%	58–63%

VI. Discussion

Integrating low-grade heat sources into CVCAS reduces dependency on grid electricity and cuts greenhouse gas emissions. Solar energy offers the highest sustainability but is weather-dependent. Geothermal and waste heat provide stable performance and quick return on investment, particularly in industrial zones. Advanced control systems and seasonal thermal storage can further enhance effectiveness.

VII. Conclusion

The expanded CVCAS configurations significantly outperform traditional VCRS in both energy and economic aspects. When powered by renewable or waste heat, CVCAS becomes a robust solution for sustainable refrigeration, particularly for the pharmaceutical and healthcare sectors. From a policy perspective, adopting such hybrid systems aligns with future economic resilience and low-carbon development strategies. Policymakers and industries should consider incentivizing these technologies to achieve long-term energy and climate goals while fostering green economic transitions.

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