Exergy Analysis of Heat Pump Systems: A Review of Methodologies, Refrigerant Comparisons, and Performance Enhancement Strategies

[1]Senthil Kumar. B, [2]Akash. C, [3]Dinesh. A, [4]Kishaanth. C. S
[1]Assistant Professor, [2]UG Student, [3]UG Student, [4]UG Student
Department of Mechanical Engineering
Sri Ramakrishna Engineering College, Coimbatore, India

Abstract — This review paper synthesizes and critically examines research on exergy analysis applied to heat pump systems, drawing from five key studies spanning experimental, simulation, and advanced analytical approaches. The reviewed works collectively address three major themes: the exergy performance of solar-assisted heat pumps with alternative refrigerants, thermodynamic optimization of solar-assisted space heating systems, and advanced exergy-based methodologies for characterizing and improving system irreversibilities. Across all studies, the evaporator or solar collector–evaporator assembly emerges as the primary site of exergy destruction, regardless of the system configuration or working fluid employed. Advanced exergy analysis techniques—decomposing irreversibilities into avoidable/unavoidable and endogenous/exogenous portions—provide substantially richer guidance for system improvement than conventional first- or second-law assessments alone. Comparative studies involving refrigerants R22, R433A (R290/R1270 blend), R410A, and R134a reveal meaningful differences in component-level efficiency and system-wide exergy destruction rates, influenced by thermophysical properties, environmental profiles, and operating conditions. Simulation-based investigations further demonstrate the role of collector type, storage tank sizing, and heat exchanger temperature differences in determining overall system COP and exergetic efficiency. Identified research gaps include limited exploration of dynamic seasonal performance, the absence of advanced exergy analysis for solar-integrated systems, and inadequate attention to hydrocarbon refrigerant safety integration. This review is intended to serve as a consolidated reference for researchers and engineers working toward thermodynamically efficient and environmentally responsible heat pump systems.

Keywords — Exergy analysis, heat pump, solar-assisted heat pump, COP, refrigerant comparison, advanced exergy, irreversibility, exergoeconomic analysis, R22, R433A, R410A, R134a, space heating.

I. INTRODUCTION

Heat pumps represent one of the most energy-efficient technologies for heating applications, capable of delivering several units of thermal energy for each unit of electrical energy consumed. Their relevance in the context of growing global energy demand and environmental constraints cannot be overstated. When integrated with renewable energy sources—particularly solar energy—heat pump systems offer a compelling pathway for reducing both fossil fuel dependence and greenhouse gas emissions. However, realizing the full potential of these systems demands a thorough understanding of where and how energy quality is degraded within each subsystem component.

The first law of thermodynamics, while adequate for energy quantity accounting, is insufficient for identifying the sources and magnitudes of thermodynamic inefficiencies. The second law, through the concept of exergy—defined as the maximum useful work extractable from a system in relation to a defined dead state—provides the framework for locating irreversibilities. Exergy analysis therefore serves as a powerful diagnostic tool, enabling engineers to rank components by their contribution to overall system inefficiency and to identify optimization priorities.

The body of literature on heat pump exergy analysis spans a broad range of system configurations, including direct-expansion solar-assisted heat pumps (DXSAHP), indirect-expansion solar-assisted heat pumps for space heating, and air-source heat pumps for residential applications. Within these configurations, researchers have investigated the influence of refrigerant choice, collector type, storage tank sizing, operating mode variation, and advanced thermodynamic decomposition methods on system performance.

This review synthesizes and critically analyzes five notable research contributions in this domain. Rather than summarizing each work in isolation, the paper groups findings thematically across (1) refrigerant selection and its exergetic consequences, (2) system configuration and simulation-based performance assessment, and (3) advanced exergy-based methodologies and their implications for system improvement. A comparative analysis table is provided to facilitate cross-study evaluation. Research gaps and limitations identified across the reviewed works are discussed, followed by conclusions that consolidate the principal insights.

The primary sources informing this review are: Paradeshi et al. (2018), who experimentally assessed R22 versus R433A in a DXSAHP system using artificial neural network (ANN) models; Cervantes and Torres-Reyes (2002), who conducted experimental exergy optimization of a solar-assisted heat pump; Atmaca and Kocak (2014), who theoretically simulated energy and exergy performance of an indirect-expansion solar-assisted space heating system; Voloshchuk et al. (2020), who applied advanced exergy, exergoeconomic, and exergoenvironmental analyses to an air-source R134a heat pump; and Voloshchuk (2017), who demonstrated advanced exergetic analysis for a wastewater-source heat pump operating in variable seasonal modes.

II. LITERATURE REVIEW AND DISCUSSION

A. Refrigerant Selection and its Exergetic Consequences

A central concern across multiple studies is the refrigerant employed in the heat pump cycle, as the thermophysical properties of the working fluid fundamentally govern the distribution and magnitude of exergy destruction within system components. The most detailed refrigerant-comparative study in the reviewed literature is by Paradeshi et al. (2018), who experimentally evaluated R22 against R433A—a binary mixture of R290 (propane) and R1270 (propylene) in a 70:30 mass ratio—within a direct-expansion solar-assisted heat pump (DXSAHP) system. The experiments were conducted under actual meteorological conditions at Calicut, India, ensuring that the results reflect realistic operational environments rather than idealized laboratory conditions.

Paradeshi et al. (2018) found that R433A exhibited approximately 8.75% lower total system exergy destruction compared to R22, with average values of 1.25 kW and 1.36 kW, respectively. At the component level, R433A reduced compressor exergy destruction by about 6.8% and condenser exergy destruction by around 3.7%, attributable primarily to its lower vapor pressure (approximately 3.8% less than R22) and hence a lower compression ratio. The reduction in compression ratio improves compressor volumetric efficiency and reduces irreversibilities associated with high-pressure operation.

However, a notable reversal was observed at the expansion valve: R433A exhibited higher exergy destruction (average 0.34 kW) compared to R22 (0.23 kW). The authors attributed this to the higher pressure differential experienced by the thermostatic expansion valve when operating with R433A, leading to greater throttling irreversibility. This finding illustrates an important principle: a refrigerant that improves overall system exergy efficiency may simultaneously increase irreversibilities in specific components, necessitating component-level re-optimization when retrofitting existing systems.

From an environmental standpoint, R433A presents a compelling advantage. Its ozone depletion potential is zero, and its global warming potential of 20 is dramatically lower than R22's value of 1700. Furthermore, R433A is miscible with the mineral oil used in existing R22 systems, facilitating direct substitution without major system modifications. These combined thermodynamic and environmental advantages confirm R433A as a viable drop-in replacement for R22 in solar-assisted heat pump applications (Paradeshi et al., 2018).

Atmaca and Kocak (2014), working with R410A in an indirect-expansion solar-assisted space heating simulation, reported a heat pump COP of 3.01 and a system COP of 2.31. A key observation from their simulation was that the high pressure differential between the evaporator and condenser—characteristic of R410A—resulted in particularly elevated expansion valve irreversibility compared to systems using R22. This finding is consistent with the trend observed by Paradeshi et al. (2018), reinforcing the view that fluids with high operating pressure ratios impose a thermodynamic penalty at the expansion stage that must be weighed against their benefits elsewhere in the cycle. Voloshchuk et al. (2020), using R134a in an air-source heat pump, similarly noted that conventional exergy analysis alone can be misleading in identifying improvement priorities, as compressor-dominated destruction values can obscure the downstream role of heat exchanger temperature differences.

B. Solar-Assisted System Configurations and Performance Characterization

The reviewed studies encompass both direct- and indirect-expansion solar-assisted heat pump configurations, each presenting distinct exergy distribution patterns. In the direct-expansion configuration studied by Paradeshi et al. (2018) and Cervantes and Torres-Reyes (2002), the solar collector doubles as the refrigerant evaporator. This integration eliminates the intermediate heat exchanger found in indirect systems, reducing the number of components and associated irreversibilities. However, it concentrates a particularly large share of total irreversibility within the collector–evaporator assembly.

Cervantes and Torres-Reyes (2002) demonstrated through experimental investigation that the collector–evaporator is the dominant source of irreversibility in a direct-expansion system, primarily because the high exergy content of incoming solar radiation is not fully converted into refrigerant evaporation. The degree of irreversibility was shown to increase with the sol-air temperature—a combined parameter capturing solar radiation intensity, absorptance, and heat loss coefficient—such that higher solar input does not automatically translate into improved exergy performance. The authors derived expressions for optimal evaporation and condensation temperatures based on entropy minimization criteria, finding that the actual operating evaporation temperature deviated from the thermodynamic optimum by an average of 46°C. Similarly, the condenser outlet temperature departed from its optimal value by an average of 12 K, indicating that significant thermodynamic improvement potential exists in practical solar-assisted heat pump installations (Cervantes and Torres-Reyes, 2002).

For the indirect-expansion system, Atmaca and Kocak (2014) simulated an R410A-based solar-assisted space heating setup for Antalya, Turkey, incorporating evacuated, single-glazed, and double-glazed flat-plate collectors. Their simulation results demonstrated that collector type exerts a significant influence on both thermal and exergetic performance. The evacuated collector (Collector A) yielded the highest storage tank temperatures, the lowest compressor power consumption, and the highest COP, owing to its superior heat removal factor and lower heat loss coefficient. The study also revealed a nuanced relationship between storage tank mass and system performance: while a smaller tank (500 kg) produced the highest instantaneous COP, it also suffered the most severe temperature drop by end of operation, compromising thermal stability. A tank mass of 1500 kg emerged as the optimal compromise between high COP and sustained thermal capacity (Atmaca and Kocak, 2014).

Exergy destruction in the indirect system was distributed differently from direct systems. Atmaca and Kocak (2014) found the greatest irreversibility in the compressor and expansion valve for the heat pump unit alone, but when the full system—including collector, storage tank, and fan-coil—was considered, the solar collector and fan-coil unit emerged as the dominant contributors. This shift highlights the importance of system boundary definition in exergy accounting: component-level analysis restricted to the refrigerant circuit alone may underestimate the significance of auxiliary components in overall system inefficiency.

C. Advanced Exergy Analysis: Decomposing Irreversibilities for Targeted Improvement

Conventional exergy analysis identifies which components exhibit the highest destruction but does not distinguish between irreversibilities that are inherent to the technology (unavoidable) and those that can be eliminated through design or operational changes (avoidable). Nor does it differentiate between irreversibilities originating within a component (endogenous) and those caused by the performance of other components (exogenous). The advanced exergy analysis framework developed at TU Berlin addresses these limitations by decomposing total exergy destruction into these four categories and their combinations.

Voloshchuk (2017) applied this framework to a wastewater-source heat pump providing space heating in variable seasonal modes. A key methodological insight of this work is that the distribution of exergy destruction across components is not constant throughout the heating season; it varies with heat source temperature and heating demand. Single-mode analysis—such as the design or nominal operating point—can therefore yield misleading improvement priorities. Voloshchuk (2017) proposed calculating annual (whole-season) values of exergy destruction as the appropriate metric for building-integrated heat pump systems, finding that only approximately 50% of total annual exergy destruction is avoidable, with about 30–40% of this avoidable portion being exogenous in origin—attributable to interactions among components rather than to the inherent inefficiency of individual components.

A particularly important finding was that conventional analysis ranked the condenser as the most critical component for improvement, whereas advanced analysis revealed that the avoidable destruction in the compressor, condenser, and evaporator were nearly equal (approximately 303, 316, and 316 kW·hr, respectively). The throttling valve, which appeared second in conventional rankings, was shown by advanced analysis to have zero avoidable endogenous exergy destruction—meaning it cannot be improved by modifying the valve itself; its entire avoidable destruction is exogenous and can only be reduced by improving the evaporator and condenser (Voloshchuk, 2017).

Building on this foundation, Voloshchuk et al. (2020) extended the framework to simultaneously address thermodynamic, economic, and environmental performance of an air-source R134a heat pump in a Ukrainian residential context. Advanced exergetic analysis identified the evaporator as the highest-priority improvement target, accounting for 63% of avoidable exergy destruction. The advanced exergoeconomic analysis further revealed that 56% of avoidable costs belonged to the compressor—driven primarily by capital investment—while 35% belonged to the evaporator, driven by its thermodynamic inefficiency. The advanced exergoenvironmental analysis showed that approximately 70% of avoidable environmental impact was associated with the evaporator.

These findings carry a significant practical implication: reducing temperature differences across the evaporator and condenser—rather than replacing the emission heating system—constitutes the most cost-effective path to simultaneous thermodynamic, economic, and environmental improvement. The authors evaluated four improvement scenarios and found that reducing minimum temperature differences in both heat exchangers simultaneously (Case 3) yielded the greatest reductions in annual exergy destruction (31%), environmental impact (9.5%), and annual COP improvement (from 3.21 to 4.3). Crucially, these gains were achieved with only modest increases in capital investment, demonstrating that advanced exergy-based analysis enables well-directed, cost-efficient improvements that conventional analysis would not suggest (Voloshchuk et al., 2020).

D. Role of Simulation and Predictive Modeling

An important methodological dimension across the reviewed studies is the use of computational models to complement or extend experimental data. Paradeshi et al. (2018) developed multilayer feed-forward artificial neural network (ANN) models with a 2-10-5 architecture—two inputs (solar irradiation and ambient temperature) and five outputs representing exergy destruction and efficiency for each component—to simulate DXSAHP performance under varying ambient conditions. These models achieved a fraction of absolute variance (R^2) consistently above 0.99 for both refrigerants across all components, confirming high predictive accuracy. The ANN approach is particularly valuable for comparing refrigerants under equivalent ambient conditions, since experimental data for two fluids cannot be collected simultaneously.

Atmaca and Kocak (2014) employed a physics-based simulation model incorporating solar radiation models from Duffie and Beckman, quasi-steady-state heat pump cycle equations, and transient storage tank energy balances. This simulation platform enabled parametric studies—varying collector type, collector area, and storage tank mass—that would be prohibitively expensive to perform experimentally. The simulation results were validated against published experimental data, showing consistent trends in COP, compressor power consumption, and exergy destruction rates across comparable configurations.

Voloshchuk (2017) and Voloshchuk et al. (2020) employed a quasi-steady-state vapor compression cycle model combined with daily weather data spanning entire heating seasons, enabling the calculation of annual exergy metrics that capture the full range of operational variability. This approach revealed that year-to-year weather variability can cause avoidable exergy destruction values to differ by as much as 14–26% from those of a middle year, underscoring the inadequacy of single-season or single-mode assessments for building-integrated systems.

III. COMPARATIVE ANALYSIS

Table 1 provides a structured comparison of the five reviewed studies across key parameters including system type, methodology, working fluid, principal findings, and identified limitations. This cross-study comparison highlights both common findings and notable divergences that emerge from differences in system configuration, climate, working fluid, and analytical approach.

Table 1: Comparative Summary of Reviewed Studies on Exergy Analysis of Heat Pump Systems

Study (Author, Year)	System Type	Working Fluid	Methodology	Key Findings	Limitations / Gaps
Paradeshi et al. (2018)	Direct-expansion solar-assisted HP (DXSAHP)	R22, R433A (R290/R1270, 70:30)	Experimental + ANN simulation	R433A shows 8.75% lower system exergy destruction; collector–evaporator is primary loss site for R22; R433A causes higher expansion valve losses; ANN (R^2>0.99) accurately predicts component exergy.	Short experimental window (Jan–Apr); no long-term seasonal analysis; flammability aspects of R433A not addressed; no economic or environmental analysis.
Cervantes & Torres-Reyes (2002)	Direct-expansion solar-assisted HP (DXSAHP)	R22	Experimental + thermodynamic optimization	Collector–evaporator is dominant irreversibility source; actual evaporation temp deviates 46°C from optimum; condenser outlet deviates 12 K; optimal temperatures derived from entropy minimization.	Small uncovered collector (4.5 m²); single refrigerant studied; no component-wise exergy efficiency reported; wind effects are empirically fitted only.
Atmaca & Kocak (2014)	Indirect-expansion solar-assisted HP, space heating	R410A	Simulation (physics-based)	System COP = 2.31, HP COP = 3.01; solar collector and fan-coil show highest improvement potential in full system; evacuated collector outperforms glazed types; 1500 kg tank provides best thermal stability.	Only conventional exergy analysis used; simulation not validated with own experimental data; single climate (Antalya); no advanced exergy decomposition; R410A has high GWP.
Voloshchuk et al. (2020)	Air-source HP for space heating	R134a	Advanced exergy + exergoeconomic + exergoenvironmental (seasonal)	Evaporator accounts for 63% of avoidable exergy destruction; compressor has highest avoidable cost (56%); reducing heat exchanger ΔT more effective than replacing emission system; annual exergy destruction reduced by 31% in best case; COP improved from 3.21 to 4.3.	Single-building case study; R134a has moderate GWP; no solar integration; economic data location-specific to Ukraine; advanced environmental indicator (Eco-indicator 99) may be outdated.
Voloshchuk (2017)	Wastewater-source HP for space heating	R134a	Advanced exergetic analysis (seasonal, multi-year)	Only ~50% of annual exergy destruction is avoidable; throttling valve has zero avoidable	Restricted to thermodynamic analysis only (no cost or environmental); single

Study (Author, Year)	System Type	Working Fluid	Methodology	Key Findings	Limitations / Gaps
				endogenous destruction; advanced analysis overturns conventional ranking of improvement priorities; year-to-year variability causes 14–26% deviation in avoidable destruction values.	building archetype; wastewater source temperature range limited to 12–22°C; no refrigerant comparison.

Several cross-cutting trends emerge from Table 1. First, the evaporator or collector–evaporator assembly is consistently identified as a critical loss component across all configurations and refrigerants. Whether assessed through conventional or advanced methods, and regardless of system type or working fluid, heat exchange irreversibilities at the low-temperature side of the cycle represent the largest or most significant improvement opportunity. This convergence across methodologically diverse studies strongly supports prioritizing evaporator optimization in heat pump design and retrofitting.

Second, advanced exergy analysis consistently reveals that the compressor's apparent dominance in conventional analysis is partly an artifact of its central role in the cycle, and that a substantial fraction of compressor irreversibility is exogenous—driven by conditions imposed by the evaporator and condenser. Improvements to the heat exchangers therefore yield double benefits: direct reduction of their own irreversibilities and indirect reduction of compressor-related losses (Voloshchuk, 2017; Voloshchuk et al., 2020).

Third, significant differences in optimal operating conditions exist across system types. Direct-expansion systems operating with solar collectors are highly sensitive to instantaneous meteorological conditions, requiring robust control strategies to approach optimal evaporation temperatures. Indirect systems offer greater thermal buffering through storage tanks, at the cost of additional heat exchanger irreversibilities. The choice between these configurations should be guided by the relative importance of component-level thermodynamic efficiency versus system-level thermal stability for a given application.

IV. RESEARCH GAPS

A critical examination of the five reviewed works reveals several important areas where current knowledge is incomplete or where methodological limitations constrain the generalizability of findings.

Absence of advanced exergy analysis in solar-assisted systems: The most analytically sophisticated tools—splitting exergy destruction into avoidable/unavoidable and endogenous/exogenous portions—have not been applied to DXSAHP or indirect solar-assisted heat pump systems. All solar-integrated studies in this review (Paradeshi et al., 2018; Cervantes and Torres-Reyes, 2002; Atmaca and Kocak, 2014) employ only conventional exergy analysis, which cannot distinguish between improvable and inherently unavoidable losses. Applying advanced exergy analysis to solar-assisted configurations could reveal whether the large irreversibilities attributed to the collector–evaporator are genuinely reducible or whether they reflect fundamental physical constraints of solar energy conversion.

Limited seasonal and multi-year performance assessment for solar systems: Dynamic operational mode variation is a central challenge in building-integrated heat pumps, as demonstrated by Voloshchuk (2017) and Voloshchuk et al. (2020) for non-solar systems. Yet the solar-assisted configurations studied by Paradeshi et al. (2018) and Cervantes and Torres-Reyes (2002) were assessed over short experimental campaigns (approximately two months), and Atmaca and Kocak (2014) modeled only select winter months. Comprehensive annual or multi-year exergy analyses of solar-assisted systems are absent from the literature, leaving the effects of seasonal solar variability on system-wide irreversibility distributions uncharacterized.

Refrigerant safety and retrofit constraints: Paradeshi et al. (2018) identified R433A as a technically superior and environmentally favorable alternative to R22, but the reviewed literature does not address the practical safety considerations associated with hydrocarbon refrigerant use, particularly regarding flammability risk in retrofitted systems with existing R22 components. Design guidelines for safe implementation of hydrocarbon blends in solar-assisted heat pump systems—including charge quantity limitations, ventilation requirements, and leak detection measures—are not covered by any of the reviewed works.

Integration of economic analysis with environmental and thermodynamic assessment in solar systems: Voloshchuk et al. (2020) demonstrated the power of simultaneous exergoeconomic and exergoenvironmental analysis for an air-source system. No equivalent analysis has been performed for solar-assisted configurations, where the economics of solar collectors, thermal storage, and associated infrastructure add further complexity and where environmental benefits of solar energy displacing grid electricity are directly relevant.

Refrigerant diversity: The reviewed literature covers R22, R433A, R410A, and R134a. Notably absent are analyses involving newer low-GWP fluids such as R32, R1234yf, R1234ze, and CO_2 (R744), which are increasingly prominent in the heat pump industry due to regulatory pressure to phase down hydrofluorocarbons. Exergy analyses of solar-assisted or advanced exergy analyses of space-heating systems using these fluids would be highly relevant to current engineering practice.

Validation of simulation models against long-term field data: While Atmaca and Kocak (2014) validated their simulation against published experimental results, and Voloshchuk (2017) and Voloshchuk et al. (2020) used weather data from institutional sources, none of the reviewed computational studies was validated against long-term field monitoring data from actual residential or commercial installations. Such validation is essential for ensuring that model predictions of seasonal exergy destruction and COP translate reliably to real-world performance.

V. CONCLUSION

This review has synthesized findings from five research contributions on exergy analysis of heat pump systems, spanning experimental investigations, simulation-based parametric studies, and advanced analytical frameworks. The following principal observations emerge from this consolidated examination:

The evaporator or solar collector–evaporator assembly is consistently the most significant site of exergy destruction across all system types, refrigerants, and analytical methods. This convergence constitutes one of the most robust conclusions in the heat pump exergy literature and should guide engineering priorities in both the design of new systems and the retrofitting of existing ones. Irreversible heat transfer processes in this component—arising from large temperature differences between the heat source and the working fluid—represent the primary thermodynamic constraint on heat pump performance.

Refrigerant choice has a measurable and non-uniform effect on exergy destruction across system components. R433A (a hydrocarbon blend of R290 and R1270) demonstrated overall thermodynamic superiority over R22 in a DXSAHP configuration, with lower exergy destruction at the compressor and collector–evaporator. However, the expansion valve exhibited increased losses with R433A, indicating that refrigerant substitution must be accompanied by component-level re-optimization. The zero ODP and very low GWP of R433A further support its consideration as an environmentally sound replacement for R22.

Advanced exergy analysis reveals qualitatively different—and more useful—improvement recommendations than conventional analysis. By separating avoidable from unavoidable irreversibilities and isolating endogenous from exogenous contributions, advanced analysis shows that a large fraction of compressor and throttling valve losses can be reduced not by modifying those components directly, but by reducing temperature differences across the heat exchangers. This finding, demonstrated independently for both wastewater-source and air-source heat pump systems, has important design implications.

System configuration parameters—including collector type, storage tank capacity, and operating mode—significantly influence the distribution of exergy destruction. Evacuated collectors and appropriately sized thermal storage enable higher COP and more stable operation. Seasonal and year-to-year variability in weather conditions can alter avoidable exergy destruction values by 14–26%, underscoring the inadequacy of single-mode or single-season analyses for heat pumps serving building thermal loads.

Simultaneous thermodynamic, economic, and environmental analysis through advanced exergoeconomic and exergoenvironmental frameworks provides the most complete basis for improvement decisions. Reducing heat exchanger temperature differences achieves improvements across all three dimensions—thermodynamic efficiency, operating cost, and environmental impact—with only modest increases in capital investment, demonstrating that these objectives need not conflict.

Overall, the reviewed literature establishes exergy analysis as an indispensable tool for heat pump system evaluation and improvement. Future research should extend advanced exergy analysis to solar-assisted configurations, incorporate comprehensive seasonal assessments, and include emerging low-GWP working fluids to keep pace with evolving industrial and regulatory contexts.

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