Thermo-Environmental Performance Analysis of Cascade Refrigeration System on Cruise Ship Applications

Deva Natasya[1], Fajri Ashfi Rayhan[2*]

(Received: 25 March 2026 / Revised: 26 March 2026 / Accepted: 30 March 2026 / Available Online: 30 March 2026)

Abstract**—** Cruise ships require substantial cooling and refrigeration capacity, which contributes significantly to onboard energy consumption, operational costs, and greenhouse gas emissions. Improving refrigeration-system performance is therefore essential to support efficient and environmentally sustainable maritime operations. This study evaluates the thermo-environmental performance of a cascade refrigeration system for cruise ship applications and identifies suitable refrigerant pairs under varying operating temperatures. A thermodynamic model was developed using mass, energy, and exergy balance equations. Simulations were conducted for several refrigerant combinations over an operating-temperature range of 275-295 K. System performance was assessed using exergy efficiency, the Ecological Coefficient of Performance (ECOP), and the Total Equivalent Warming Impact (TEWI). The results show that increasing the operating temperature reduces exergy efficiency and ECOP for all refrigerant pairs, while TEWI increases due to higher energy-related emissions. Among the investigated refrigerant pairs, R152a/R290 demonstrated the best overall performance, followed by R600a/R290, owing to their higher thermodynamic efficiency and lower environmental impact. In contrast, CO2-based combinations, particularly R717/R744, showed comparatively poorer performance and greater sensitivity to temperature increases. These findings highlight the importance of refrigerant selection in improving the performance of cascade refrigeration systems for cruise ship applications.

Keywords— cascade refrigeration; ECOP; exergy efficiency; marine cooling system; TEWI.

**Corresponding Author: fajri.ar@upnvj.ac.id*

I. Introduction

The maritime sector faces increasing pressure to cut greenhouse gas (GHG) emissions and boost energy efficiency due to international environmental rules, especially those set by the International Maritime Organization (IMO) under MARPOL Annex VI. This regulatory structure sets limits on nitrogen oxides (NOx) and sulfur oxides (SOx) emissions and includes energy-efficiency measures like the Energy Efficiency Design Index (EEDI) and the Energy Efficiency Existing Ship Index (EEXI) [1]. Additionally, the Carbon Intensity Indicator (CII) requires ships to continuously improve their carbon-emission performance throughout their operational life cycle. These regulations suggest that ship energy optimization should not focus only on propulsion systems but also include auxiliary systems that significantly contribute to onboard energy consumption and environmental impact emissions [2].

Among various ship types, cruise ships are some of the most energy-intensive vessels because they serve not only as transportation systems but also as floating hospitality facilities. Their operation involves a significant hotel load related to passenger comfort, food preservation, lighting, ventilation, and air-conditioning services [3]. In this context, cooling and refrigeration systems are especially important because they are essential for maintaining indoor thermal comfort, preserving food and beverages, and ensuring the reliable operation of technical spaces and onboard facilities. The complexity of cooling demand increases in large and densely occupied spaces, such as atriums, restaurants, theatres, and accommodation zones, where thermal load variations are more significant [4]. Previous studies have shown that hotel loads make up a significant portion of total onboard energy use and are therefore closely linked to the overall environmental performance of cruise ships [5]. Supporting generators usually run continuously at fairly steady loads, often around 1 MW, showing the high energy demand of auxiliary systems [6]. Recent studies have also stressed that hotel and auxiliary systems should be regarded as essential parts of maritime decarbonization strategies, not just secondary energy consumers [7].

The importance of refrigeration systems on cruise ships goes beyond just energy use. These systems also impact the environment through refrigerant leaks during operation, maintenance, and disposal. Conventional hydrofluorocarbon (HFC) refrigerants are well known for their high Global Warming Potential (GWP), which adds to the direct climate impact of refrigeration systems. [8][9]. Therefore, the environmental performance of a refrigeration system should be assessed from two connected perspectives: indirect emissions from energy use and direct emissions from refrigerant leaks. This dual approach has increased interest in refrigeration technologies that aim for high thermodynamic efficiency and reduced environmental impact through the use of more sustainable refrigerants [10].

Deva Nataya, Naval Architecture, Faculty of Engineering, Universitas Pembangunan Nasional Veteran Jakarta, Indonesia. E-mail: 2210313020@mahasiswa.upnvj.ac.id
Fajri Ashfi Rayhan, Naval Architecture, Faculty of Engineering, Universitas Pembangunan Nasional Veteran Jakarta, Indonesia. E-mail: fajri.ar@upnvj.ac.id

To overcome the limitations of traditional single-stage refrigeration systems in large temperature-lift conditions, advanced refrigeration technologies have been widely explored. One of the most promising solutions is the cascade refrigeration system (CRS), especially suitable for applications needing a wide temperature gap between the cooled space and the surrounding environment. A cascade refrigeration system includes two interconnected vapor-compression cycles, known as the low-temperature cycle (LTC) and the high-temperature cycle (HTC), connected through a cascade heat exchanger. This setup enables each cycle to operate within a more suitable temperature range, which enhances system performance, lowers compressor stress, and makes it more appropriate for low-temperature applications [11][12]. Because cruise ships need continuous and reliable cooling under changing operational and environmental conditions, CRS has strong potential to enhance refrigeration performance in maritime applications.

Several studies have examined cascade refrigeration systems from various thermodynamic angles. Earlier research has shown the feasibility of CRS through energy and exergy analyses, focusing on refrigerant pair selection, compressor work, and system efficiency. [13][14]. Exergy analysis is especially important because it offers a deeper understanding of thermodynamic irreversibility than conventional energy analysis, enabling clearer identification of losses in individual system components. Exergy analysis is especially important because it offers a deeper understanding of thermodynamic irreversibility than conventional energy analysis, enabling clearer identification of losses in individual system components [15]. In refrigeration systems, irreversibility can occur in compressors, condensers, evaporators, expansion valves, and especially in the cascade heat exchanger, where temperature differences greatly affect overall system performance. Therefore, using exergy-based evaluation is a helpful method for assessing how efficiently a cascade refrigeration system uses energy resources under various operating conditions.

Besides thermodynamic efficiency, the environmental aspect of cascade refrigeration systems has gained more attention, especially when it comes to refrigerant choice. The use of low-GWP and zero-ODP refrigerants has become a key factor in design due to stricter environmental regulations and the need to lessen the long-term climate impact of refrigeration technologies [10][14]. Recent studies have shown that refrigerant choice significantly impacts not only the coefficient of performance and exergy efficiency but also the overall environmental impact of the system throughout its operational lifetime [16][17]. This issue is especially important for cruise ship applications, where refrigeration systems run continuously and cumulative effects from electricity use and refrigerant leaks can become significant.

Although previous studies have offered valuable insights into cascade refrigeration systems, many have evaluated system performance from only one or two perspectives, often under limited operating conditions or for specific refrigerant combinations [18]. In several cases, thermodynamic analysis and environmental assessment are addressed separately, which makes it difficult to obtain an integrated view of system behavior. Additionally, studies specifically focused on cruise ship applications remain relatively scarce. Therefore, the problem addressed in this study is the limited availability of an integrated thermo-environmental assessment of cascade refrigeration systems for cruise ship applications under various operating conditions and refrigerant choices.

In this context, exergy analysis, the Ecological Coefficient of Performance (ECOP), and Total Equivalent Warming Impact (TEWI) offer a relevant basis for thermo-environmental assessment. Exergy analysis evaluates thermodynamic irreversibility, ECOP reflects ecological performance from a second-law perspective [19], and TEWI evaluates the total environmental impact by considering both direct refrigerant emissions and indirect emissions related to energy use [20].

When considered together, these indicators can offer a more integrated basis for assessing cascade refrigeration system performance than traditional energy-based measures alone. Another point emphasized in the literature is the effect of operating parameters on cascade refrigeration performance. Previous studies have shown that evaporator temperature, condenser temperature, cascade temperature, refrigerant mass flow rate, and working-fluid selection influence thermodynamic efficiency, exergy destruction, compressor power requirements, and environmental impact [16][17][21][22]. Since cruise ship refrigeration systems operate under changing thermal demands and environmental conditions, examining the influence of these factors is important for understanding their behavior in maritime applications.

Given the identified gaps, this study proposes an integrated assessment of cascade refrigeration systems in cruise ships using exergy, ECOP, and TEWI as the primary performance indicators. The innovation of this research lies in the simultaneous application of these three indicators within a single analytical framework to evaluate thermodynamic behavior and environmental impact. Specifically, exergy analysis is used to assess thermodynamic irreversibility, ECOP evaluates ecological performance from a second-law perspective, and TEWI quantifies the overall environmental burden related to refrigerant leakage [19][20]. Additionally, the effects of operating conditions, including temperature, refrigerant mass flow rate, and working fluid selection, are examined, since previous studies have shown that these parameters strongly influence cascade refrigeration performance. Additionally, the effects of operating conditions, including temperature, refrigerant mass flow rate, and working fluid selection, are examined, since previous studies have shown that these parameters strongly influence cascade refrigeration performance [7][15][22]. Therefore, this study aims to offer a more thorough foundation for evaluating the thermodynamic and environmental performance of cascade refrigeration systems in maritime applications using exergy, ECOP, and TEWI.

II. METHOD

A. Object of Research

A cruise ship can be seen as a complex "floating city" that combines propulsion, energy systems, and extensive hotel amenities, leading to high and continual energy demand. Among onboard systems, cooling and refrigeration are vital, as they greatly influence overall energy use, fuel consumption, and environmental emissions [23][24]. The rising demand for thermal comfort, especially for air conditioning and refrigeration, makes these systems the main energy consumers in cruise ship operations. In this study, Vision of the Seas, a Royal Caribbean cruise ship built in 1998, is chosen as the case study. The vessel, measuring 279 meters in length, with a gross tonnage of 78,717 GT, and an average voyage length of 8 days, exemplifies a typical cruise ship with high and consistent cooling requirements [25]. It is equipped with a propulsion system of 2 × 25,200 kW and an air conditioning system with a cooling capacity of 10,010 kW, emphasizing the importance of auxiliary cooling loads.

Given the limitations of traditional refrigeration systems in managing wide temperature ranges and their environmental effects, this study explores the use of a cascade refrigeration system (CRS). System performance is assessed through thermodynamic and environmental metrics, specifically the Ecological Coefficient of Performance (ECOP) and Total Equivalent Warming Impact (TEWI), to promote more efficient and sustainable cruise ship operations.

B. Machine Schematic

The cooling system analyzed in this study uses a cascade refrigeration setup with two linked cycles: the High Temperature Cycle (HTC) and the Low Temperature Cycle (LTC), which are connected via a cascade condenser. The system design is based on a configuration developed in previous research [26]. The system includes two compressors, one condenser, one evaporator, one cascade condenser, three expansion valves, two flash chambers, and four internal heat exchangers (HEw, HEx, HEy, and HEz). Adding internal heat exchangers improves heat transfer efficiency and boosts overall system performance by decreasing irreversibilities. A schematic diagram of the cascade refrigeration system studied here is shown in Figure 1.

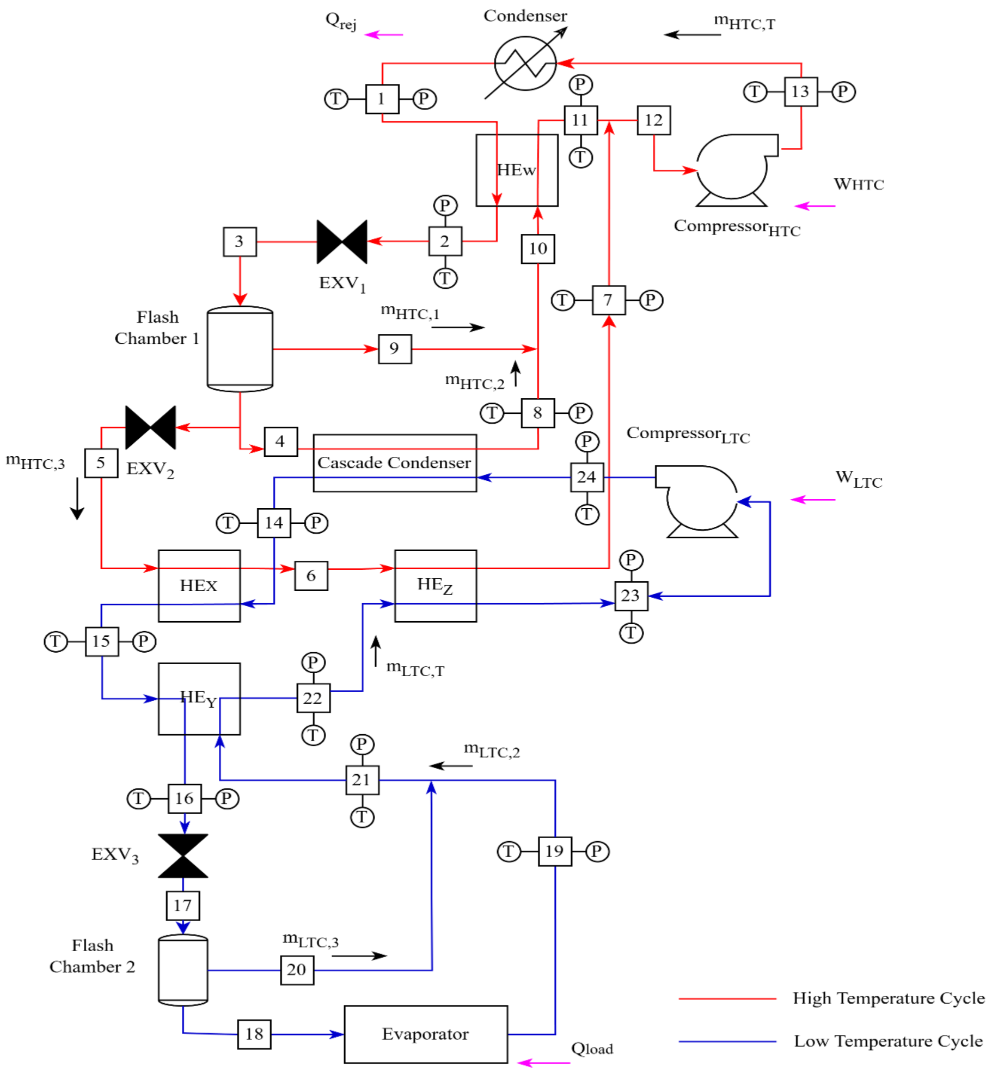

Figure 1. Machine Schematic

C. Analysis Parameter Specifications

The operating conditions of the cascade refrigeration system are set by specifying the evaporation and condensation temperatures for both the High Temperature Cycle (HTC) and the Low Temperature Cycle (LTC), as well as the cascade condenser temperature that thermally connects the two cycles. These temperature levels are chosen based on the operating limits of the refrigerants and the overall system characteristics. A detailed summary of the temperature parameters is provided in Table 1. Additionally, the mass flow rates are fixed at 1.3 kg/s for the HTC and 0.5 kg/s for the LTC to ensure a consistent basis for performance evaluation across different operating conditions. This method allows for a more reliable comparison of system behavior when examining the effects of various operating parameters.

To evaluate both thermodynamic and environmental performance, several low-GWP refrigerants are considered, including R1234yf, R290 (propane), R717 (ammonia), R152a, R600a (isobutane), and R744 (CO_2). These refrigerants are chosen for their potential as environmentally friendly alternatives to traditional high-GWP refrigerants, along with their varied thermodynamic properties and safety features, such as flammability, toxicity, and operating pressure. Previous studies have shown that natural refrigerants, especially R744 and R290, are among the most widely used options in ultra-low-GWP applications (<150) [27]. In cascade refrigeration systems, the R744–R717 (LTC–HTC) configuration is one of the most thoroughly studied because of its high efficiency and suitability for low-temperature uses. Additionally, previous research has assessed the thermodynamic performance of cascade systems by analyzing how key operating parameters—such as evaporation temperature, condensation temperature, superheating, and subcooling—affect system efficiency, especially in terms of the coefficient of performance (COP) [28]. Furthermore, experimental studies comparing low-GWP refrigerants—such as R152a, R1234yf, R290, R600a, and R744—support the importance of selecting these working fluids for comprehensive performance and energy analyses, as they serve as alternatives to conventional refrigerants like R134a [29]. These studies verify that choosing the right refrigerant is crucial in affecting both system efficiency and environmental impact.

TABLE 1.
PARAMETER TEMPERATURE

Parameters	Range
Condensation Temperature	313 [K]
Evaporation Temperature	233 [K]
Ambient Temperature	298 [K]
Subcooling Temperature of Heat Exchanger (w)	275 [K] – 295 [K]
Temperature Subcooling Heat Exchanger (x)	275 [K] – 295 [K]
Subcooling temperature of heat exchanger (y)	275 [K] – 295 [K]
Superheating temperature of heat exchanger (x)	275 [K] – 295 [K]
Desuperheating temperature of the heat exchanger (z)	275 [K] – 295 [K]

D. Thermodynamic Model

The thermodynamic analysis in this study is based on the first law of thermodynamics, using mass and energy balance equations for each system component to calculate the heat transfer rate and compressor work. The overall system performance is then evaluated using exergy efficiency and the Ecological Coefficient of Performance (ECOP). Additionally, the environmental impact is assessed through the Total Equivalent Warming Impact (TEWI) approach, which accounts for both direct emissions from refrigerant leakage and indirect emissions from electricity consumption throughout the system's operational lifetime. [26] [16].

Mass conservation equations are applied to confirm that the refrigerant flow in each system component stays balanced without any mass building up during the process. The mass conservation equation is written as follows:

$$\sum m_{in} = \sum m_{out} \tag{1}$$

In equation (1), $\sum m_{in}$ represents the total mass flow rate entering a system component, while $\sum m_{out}$ denotes the total mass flow rate leaving the component. The variable m indicates the refrigerant mass flow rate (kg/s), and the summation symbol $\sum$ refers to the total of all relevant mass flow contributions. The subscripts "in" and "out" specify the inlet and outlet states of the component under consideration.

The energy conservation equation, which is based on the first law of thermodynamics, is used to assess the energy balance of each system component. Under steady-state conditions and ignoring changes in kinetic and potential energy, the energy entering the system equals the sum of heat transfer and work. This relation is employed to determine heat transfer rates and compressor work. Generally, the energy conservation equation can be written as follows:

$$Q - W = \sum m_{out} h_{out} - \sum m_{in} h_{in} \quad (2)$$

In equation (2), Q (kW) is the rate of heat transfer into the system, W (kW) is the work done by the system, and h (kJ/kg) is the specific enthalpy.

The exergy conservation equation, based on the second law of thermodynamics, is used to analyze the exergy balance in a system. Under steady-state conditions, the difference between the incoming and outgoing exergy equals the exergy lost due to irreversibility, allowing for the assessment of system component efficiency. The exergy equation is as follows:

$$E\dot{x}_i = m[(h_i - h_0) - T_0(s_i - s_0)] \quad (3)$$

Equation (3) is used to calculate the exergy flow rate of a fluid at a point within the system. In this equation,m is the mass flow rate, while h_i and s_i denote the specific enthalpy and entropy under actual conditions. The values h_0 and s_0 represent the environmental reference conditions (dead state), i.e., when the fluid no longer has the potential to perform work. The ambient temperature T_0 is used to determine the effect of entropy on the unusable exergy.

The cooling exergy rate equation $E\dot{x}_{cooling}$ is used to express the maximum work potential obtainable from the heat transfer process in a cooling system relative to the environment. The cooling exergy rate equation is expressed as follows:

$$E\dot{x}_{cooling} = \left(\frac{T_0 - T_{evap}}{T_{evap}}\right) Q_{load} \quad (4)$$

In this equation, T_0 represents the ambient temperature (dead state), while T_{evap} is the evaporation temperature at the evaporator. Q_{load} indicates the cooling load supplied by the system. The factor $\left(\frac{T_0 - T_{evap}}{T_{evap}}\right)$ describes the temperature difference between the system and the environment, which affects the magnitude of exergy loss.

Equation (4) is used to show the relationship between the exergy rate entering the system $E\dot{x}_{in}$ and the total net power $\dot{W}_{net}$, which is the sum of the power from the low-temperature cycle (LTC) and the high-temperature cycle (HTC).

$$E\dot{x}_{in} = \dot{W}_{net} = \dot{W}_{LTC} + \dot{W}_{HTC} \quad (5)$$

In this equation, $\dot{W}_{LTC}$ and $\dot{W}_{HTC}$ represent the power generated by the low-temperature cycle and the high-temperature cycle, respectively. The system's total net power $\dot{W}_{net}$ is the sum of the power from both cycles.

Equation (5) is used to calculate the exergy efficiency in a cooling system involving exergy flow rates. The equation can be expressed as follows:

$$\eta_{II} = \frac{E\dot{x}_{cooling}}{E\dot{x}_{in}} \quad (6)$$

In this equation, the exergy loss rate $E\dot{x}_{cooling}$ indicates the exergy loss or exergy loss during the cooling process, while the exergy input rate $E\dot{x}_{in}$ represents the exergy entering the system. The exergy efficiency η_{II} is used to assess how effectively the system utilizes the incoming exergy to produce the desired benefit, namely the cooling process.

Furthermore, the *Ecological Coefficient of Performance* (ECOP) equation is as follows:

$$ECOP = \frac{Q_{load}}{E\dot{x}_{des,Total}} \quad (7)$$

Equation (5) is used to evaluate the performance of a cooling system based on exergy analysis. The "Q_{load} " represents the cooling load or the amount of heat absorbed from the cooled space, while the $E\dot{x}_{des,Total}$ is the total exergy lost within the system due to the irreversibility of the process. The smaller the exergy loss, the higher the ECOP value, indicating that the system operates more efficiently in utilizing exergy to produce the cooling effect.

The *Total Equivalent Warming Impact* (TEWI) equation consists of two main components: direct emissions and indirect emissions, as shown in Equation (6).

$$TEWI = TEWI_{direct} + TEWI_{indirect} \quad (8)$$

Direct TEWI is related to the refrigerant used in the refrigeration system and represents CO_2-equivalent emissions from refrigerant leaks during operation and from refrigerant losses released into the environment during the recycling process. The direct TEWI equation is as follows:

$$TEWI_{direct} = GWP_{LTC}[L_{LTC} \, . \, N + M_{LTC}\,(1-\alpha)] + GWP_{HTC}[L_{HTC} \, . \, N + M_{HTC}\,(1-\alpha)] \quad (9)$$

In this equation, L represents the annual refrigerant leakage rate, while M indicates the total refrigerant charge in the system; both are determined by the circuit characteristics. The refrigerant recovery factor is assumed to be α = 90% for all refrigerants used. In this study, the operational life of the LTC and HTC systems is assumed to be N = 15 tahun. The annual leakage rate L is considered proportional to the refrigerant mass M, sehingga dapat dihitung dengan persamaan berikut: so it can be calculated using the following equation:

$$L_c = 0{,}15\,.\,M_c\,.\frac{1}{year} \quad (10)$$

The specific refrigerant charge mass of the circuit (M_c) is assumed to be proportional to the required cooling load at the evaporator (Q_{evap}). The estimates used refer to the method applied in previous research [30], namely 1 kg.kW^{-1} for the refrigerant in the LTC system and 2 kg.kW^{-1} for the HTC system. Based on this approach, the refrigerant masses used are 100 kg for the LTC system and 200 kg for the HTC system. Indirect emissions in TEWI are determined by the system's annual electricity consumption (E) and the applicable electricity emission factor for a given country ($\beta_{country}$), where in Indonesia the electricity emission factor in 2021 was approximately 0,7177 (kg.CO_2/kWh).

$$TEWI_{indirect} = E \cdot \beta_{country} \cdot N \quad (11)$$

III. Results and Discussion

A. Exergy Efficiency

Figure 2 shows that exergy efficiency declines progressively with increasing temperature for all examined refrigerant combinations under the operating conditions of HTC = 1.3 kg/s and LTC = 0.5 kg/s. Specifically, as the temperature rises from 275 K to 295 K, the exergy efficiency drops from 0.1088 to 0.0389 for R717/R744, from 0.2422 to 0.1667 for R1234yf/R744, from 0.1921 to 0.1089 for R290/R744, from 0.2767 to 0.1695 for R152a/R290, and from 0.2654 to 0.1628 for R600a/R290. This consistent downward trend suggests that higher operating temperatures increase thermodynamic irreversibilities within the cascade refrigeration system. From a thermodynamic standpoint, this behavior may be linked to increased compressor work, greater entropy production, and reduced heat-transfer efficiency between the low- and high-temperature stages. Consequently, a larger portion of the supplied energy becomes unavailable for useful refrigeration, resulting in lower exergy efficiency. This observation aligns with prior studies indicating that evaporation and condensation temperatures are among the most influential factors affecting the exergetic performance of cascade refrigeration systems [17].

A key finding of this study is the significant variation in exergy efficiency among the refrigerant pairs across the entire temperature range. Among all combinations, R152a/R290 consistently shows the highest exergy efficiency, with values of 0.2767, 0.2679, 0.2595, 0.2517, and 0.1695 at 275, 280, 285, 290, and 295 K, respectively. This indicates that R152a/R290 offers the best thermodynamic compatibility between the low-temperature and high-temperature cycles. The outstanding performance of this pair suggests its thermophysical properties are more effective at minimizing exergy destruction during compression and heat exchange. Additionally, R600a/R290 also demonstrates consistently high performance and ranks second among all tested combinations, further emphasizing the thermodynamic potential of hydrocarbon-based refrigerant pairs in cascade refrigeration systems. This finding is especially important because it shows that low-GWP refrigerants, particularly hydrocarbon-based fluids, can provide not only environmental benefits but also strong thermodynamic performance, as reported in previous studies [31].

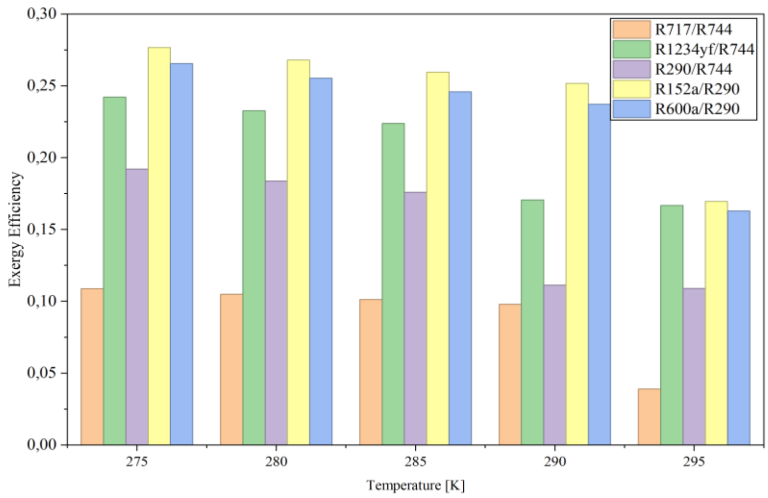

Figure 2. Exergy efficiency versus temperature for various refrigerant combinations.

The main contribution of this study is demonstrating that the effect of temperature on exergy efficiency heavily depends on the refrigerant pair used. Although all combinations see a decrease in exergy efficiency as temperature rises, the extent of this decline varies significantly among different refrigerant pairs. Notably, R717/R744 shows the greatest relative drop in exergy efficiency, while R152a/R290 and R600a/R290 maintain higher efficiency levels across the entire temperature range studied. This suggests that refrigerant choice influences not only the overall exergy efficiency but also how sensitive the system is to temperature changes. Consequently, these results highlight that the best refrigerant pair should not be chosen solely based on maximum efficiency but also on its ability to maintain good thermodynamic performance across different operating temperatures. In this context, R152a/R290 appears to be the most promising option among the pairs evaluated in this research.

In contrast, the relatively low exergy efficiency observed in the CO2-based combinations, especially R717/R744, indicates that these systems are more prone to irreversibility under the tested operating conditions. The very low exergy efficiency value of 0.0389 at 295 K for R717/R744 suggests that a significant portion of the input energy is lost through non-ideal thermodynamic processes. This behavior can be linked to the inherent characteristics of CO2-based systems, such as high operating pressure and increased sensitivity to temperature changes, which can intensify exergy destruction in key components like the compressor and heat exchanger [9]. Although R1234yf/R744 performs better than R717/R744, its exergy efficiency remains consistently lower than that of the hydrocarbon-based refrigerant pairs over the entire temperature range. These findings are in agreement with previous studies indicating that CO2-based cascade refrigeration systems often experience higher exergy destruction in key components, thereby limiting their overall thermodynamic effectiveness [9].

Overall, the present study shows that R152a/R290 is the most thermodynamically favorable refrigerant pair among the alternatives studied across the entire temperature range. Meanwhile, R600a/R290 also emerges as a strong low-GWP option with consistently high exergy efficiency. The results further confirm that increasing temperature decreases exergy efficiency in all cases; however, the degree of this decrease is strongly influenced by the refrigerant pair chosen. Therefore, the novelty of this work lies in its comparison demonstrating that hydrocarbon-based refrigerant pairs, especially R152a/R290, not only offer environmental benefits but also provide superior and more stable exergetic performance than several CO2-based alternatives under the same operating conditions. These findings may serve as a useful reference for selecting and optimizing refrigerants in future cascade refrigeration system designs.

B. *Ecological Coefficient of Performance* (ECOP)

Figure 3 shows that the ECOP decreases steadily as the temperature rises from 275 K to 295 K for all investigated working fluid combinations under the operating conditions of HTC = 1.3 kg/s and LTC = 0.5 kg/s. Specifically, the ECOP of R717/R744 drops from 0.9558 to 0.3679, R1234yf/R744 from 3.525 to 1.892, R290/R744 from 2.095 to 1.078, R152a/R290 from 4.252 to 2.166, and R600a/R290 from 4.033 to 2.052. This general downward trend confirms that increasing temperature negatively impacts the exergetic performance of the cascade refrigeration system. As the operating temperature increases, thermodynamic irreversibilities in the main system components become more pronounced, decreasing the system's ability to convert supplied energy into useful refrigeration. From an exergy perspective, this behavior is linked to higher compressor work, less effective temperature matching during heat transfer, and greater entropy generation in the condenser, evaporator, compressor, and cascade heat exchanger. As a result, the useful exergy recovered from the system declines, causing lower ECOP values. This finding aligns with previous studies showing that higher condensation or ambient temperatures lead to increased exergy destruction and reduced overall system performance [32].

A key finding of this study is the clear and consistent performance hierarchy among the tested refrigerant combinations across the entire temperature range. Among all working fluid pairs, R152a/R290 consistently shows the highest ECOP, with values of 4.252, 3.903, 3.647, 3.457, and 2.166 at 275, 280, 285, 290, and 295 K, respectively. R600a/R290 also demonstrates similarly high performance, with ECOP values decreasing from 4.033 to 2.052. The superior performance of these two low-GWP refrigerant combinations indicates that they offer more favorable thermodynamic matching between the high- and low-temperature cycles compared to the other alternatives examined here. Their higher ECOP values suggest lower exergy losses and more efficient use of available energy, likely due to better operating characteristics during compression and heat exchange. These findings support previous research indicating that refrigerants such as R290 and R600a can deliver high thermodynamic efficiency and reduced energy losses relative to conventional refrigerants [33][34][35].

The main contribution of this study is not only identifying the best-performing refrigerant pair but also demonstrating that temperature's effect on ECOP heavily depends on the specific refrigerants used. Although all examined pairs show a decline in ECOP as temperature rises, the extent of deterioration varies significantly among them. This suggests that choosing refrigerants should go beyond selecting the highest ECOP at a single operating point and include considering their ability to

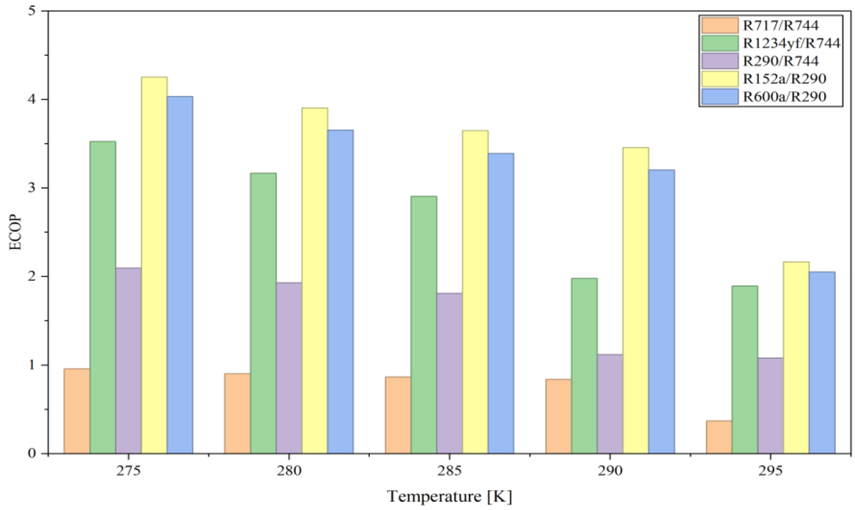

Figure 3. ECOP variation with temperature (275–295 K) for different working fluid combinations.

sustain stable thermodynamic performance across a broader temperature range. From this perspective, R152a/R290 is not only the top performer in terms of absolute ECOP but also the most thermodynamically resilient as temperature increases. R600a/R290 remains highly competitive as well, indicating that some low-GWP refrigerant pairs can offer both excellent performance and good thThe main contribution of this study is not only identifying the best-performing refrigerant pair but also demonstrating that temperature's effect on ECOP heavily depends on the specific refrigerants used. Although all examined pairs show a decline in ECOP as temperature rises, the extent of deterioration varies significantly among them. This suggests that choosing refrigerants should go beyond selecting the highest ECOP at a single operating point and include considering their ability to sustain stable thermodynamic performance across a broader temperature range. From this perspective, R152a/R290 is not only the top performer in terms of absolute ECOP but also the most thermodynamically resilient as temperature increases. R600a/R290 remains highly competitive as well, indicating that some low-GWP refrigerant pairs can offer both excellent performance and good thermal stability.

This finding emphasizes a key innovation of the present work. Instead of merely comparing refrigerant combinations, this study shows that temperature sensitivity is a critical factor influencing ECOP behavior in cascade refrigeration systems. The results indicate that the best refrigerant pair is the one that offers high ECOP while maintaining a stable response to temperature changes. This is especially important for practical applications, as refrigeration systems typically operate under varying thermal conditions rather than at a constant temperature. Consequently, the present study offers a more application-focused basis for refrigerant selection and system optimization.

In contrast, the R744-based combinations generally perform less effectively under the tested conditions. R1234yf/R744 shows intermediate ECOP values, while R290/R744 experiences greater performance degradation. The lowest ECOP values are observed for R717/R744, decreasing from 0.9558 at 275 K to 0.3679 at 295 K. This indicates that R717/R744 is more sensitive to irreversibility as temperature rises, likely due to the strong temperature dependence and high operating pressure associated with CO2-based systems. These findings support previous research indicating that the performance of R744-based cascade systems heavily depends on operating conditions and system configuration [36][37].

Overall, this study demonstrates that increasing temperature consistently lowers ECOP for all refrigerant pairs, although the extent of the reduction is highly dependent on the refrigerant. Among the tested combinations, R152a/R290 is the most promising, closely followed by R600a/R290. The primary novelty of this work is showing that certain low-GWP refrigerant pairs can achieve not only higher ECOP but also better thermodynamic stability under elevated temperatures than several R744-based options. These results offer valuable guidance for selecting and optimizing working fluids Overall, this study demonstrates that increasing temperature consistently lowers ECOP for all refrigerant pairs, although the extent of the reduction is highly dependent on the refrigerant. Among the tested combinations, R152a/R290 is the most promising, closely followed by R600a/R290. The primary novelty of this work is showing that certain low-GWP refrigerant pairs can achieve not only higher ECOP but also better thermodynamic stability under elevated temperatures than several R744-based options. These results offer valuable guidance for selecting and optimizing working fluids in cascade refrigeration systems.in cascade refrigeration systems.

C. *Total Equivalent Warming Impact* (TEWI)

The graph show that the Total Equivalent Warming Impact (TEWI) generally increases with rising temperature for all working-fluid pairs. In the temperature range of 275–285 K, the increase in TEWI is relatively gradual. For instance, the TEWI of R717/R744 increases from approximately 1.544×10^9 to 1.657×10^9,

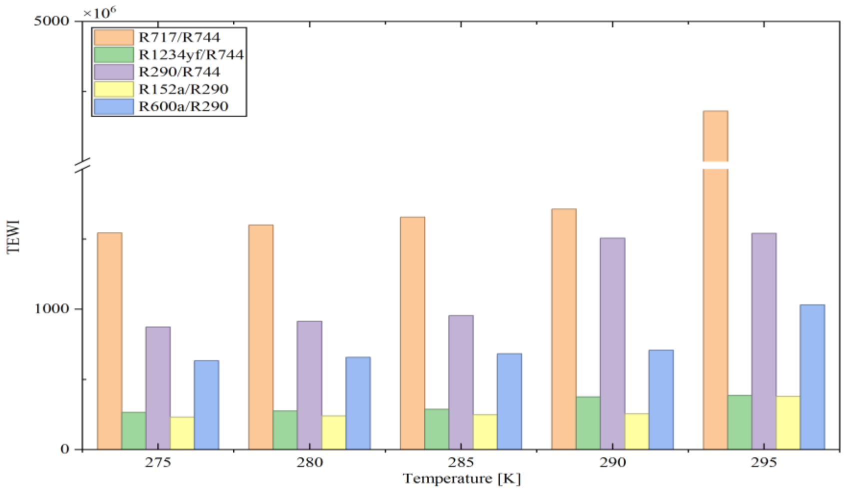

Figure 4. Effect of temperature on TEWI for various refrigerant combinations in a cascade refrigeration system.

while that of R290/R744 rises from 8.741×10^8 to 9.544×10^8. However, at higher temperatures, the increase becomes more pronounced, particularly for R717/R744, whose TEWI rises from 1.714×10^9 at 290 K to 4.361×10^9 at 295 K, representing the highest value among all tested combinations. This trend shows that raising ambient or operating temperature significantly boosts system energy use, thus increasing the indirect-emission contribution to TEWI [38].

A comparison of the working fluids reveals notable differences in environmental performance. R717/R744 consistently shows the highest TEWI across all operating conditions, indicating that this pair is the least environmentally friendly in terms of total equivalent warming impact. In contrast, the hydrocarbon-based pair R152a/R290 shows the lowest TEWI across the entire temperature range, increasing from 6.068×10^8 at 275 K to 9.906×10^8 at 295 K. At the highest temperature, R1234yf/R744 also demonstrates relatively low TEWI, reaching approximately 1.008×10^9, followed closely by R600a/R290 at 1.032×10^9. These results show that using low-GWP refrigerants can effectively lower the overall environmental impact; however, TEWI is not determined solely by refrigerant properties, as system energy consumption remains a significant factor [39].

A deeper interpretation of these results indicates that the environmental benefit of a refrigerant pair depends not only on its direct-emission potential but also on how its energy performance reacts to temperature changes. In this study, the key finding is that each refrigerant pair shows a unique TEWI–temperature response. R717/R744 exhibits the highest temperature sensitivity, with a significant increase at 295 K, suggesting that its indirect emissions become more dominant under harsher operating conditions. Conversely, R152a/R290 maintains the lowest TEWI across the entire temperature range examined, implying better environmental stability with temperature variations. Additionally, R1234yf/R744 performs competitively at higher temperatures, indicating it may provide a good balance between low direct emissions and manageable energy impact. This behavior emphasizes that refrigerant selection should go beyond GWP classification and also consider the system’s thermodynamic response at actual operating temperatures. The novelty of this work lies in showing that TEWI-based environmental assessment can distinguish not only the overall performance of different refrigerant pairs but also their sensitivity to rising temperatures, which is highly relevant for practical refrigeration system design and refrigerant choice.

This interpretation aligns with previous studies showing that the environmental performance of refrigeration systems is heavily affected by exergy characteristics and operating conditions, especially condensation temperature and other thermodynamic parameters. An increase in operating temperature can raise the exergy destruction rate by about 35–47%, indicating higher irreversibility and decreased energy efficiency [40]. This directly causes higher energy use, which ultimately raises indirect emissions in TEWI calculations.

This condition directly causes higher electricity use, which then raises the indirect-emission part of TEWI calculations. TEWI is widely recognized as a key environmental indicator because it considers both direct emissions from refrigerant leaks and indirect emissions related to energy use over the system's lifetime. This makes it a more complete measure of global warming impact [41]. Furthermore, the development of approaches like Expanded TEWI demonstrates that environmental assessment in the HVAC&R sector continues to evolve to include broader contributions beyond traditional TEWI analysis [20].

IV. CONCLUSION

This study assessed the thermal and environmental performance of a cascade refrigeration system for cruise ship use across different operating temperatures, using exergy efficiency, the Ecological Coefficient of Performance (ECOP), and the Total Equivalent Warming Impact (TEWI) as key performance indicators. The simulation results show that system performance is strongly affected by operating temperature and refrigerant choice. Generally, higher temperatures tend to reduce thermodynamic efficiency and increase environmental impact. The results also indicate that hydrocarbon-based refrigerant pairs deliver better overall performance than CO2-based options under the tested conditions.

1. As the operating temperature rose from 275 K to 295 K, both exergy efficiency and ECOP declined for all refrigerant pairs, indicating increased thermodynamic irreversibility and reduced energy efficiency within the system.
2. The rise in TEWI, especially within the 290-295 K range, shows that higher operating temperatures result in more indirect emissions due to increased energy use consumption.
3. This refrigerant combination consistently demonstrated the highest exergy efficiency and ECOP, along with the lowest TEWI, indicating the most favorable balance between thermodynamic efficiency and environmental impact.
4. As the second-best refrigerant pair, R600a/R290 offers relatively high thermodynamic efficiency and low environmental impact, making it a promising alternative for cascade refrigeration systems on cruise ships applications.
5. The results confirm that system evaluation should not depend on a single parameter but should consider both thermodynamic efficiency and environmental impact to identify the most suitable refrigerant pair.
6. Overall, the performance of a cascade refrigeration system cannot be assessed using only a single parameter; instead, it must balance energy efficiency and environmental impact.
7. Among the options examined, this refrigerant pair delivered the best thermo-environmental performance for cruise ship cascade refrigeration applications.

ACKNOWLEDGEMENTS

The author would like to thank the Naval Architecture Study Program, Faculty of Engineering, Universitas Pembangunan Nasional (UPN) Veteran Jakarta for the support and funding provided so that this research could be carried out properly.

REFERENCES

[1] M. Hero, P. Vidmar, P. Vla, and M. Perkovi, "ScienceDirect Limiting greenhouse gas emissions in the maritime transport sector," vol. 83, pp. 157–164, 2025, doi: 10.1016/j.trpro.2025.02.022.

[2] Q. Yuan, S. Wang, and J. Peng, "Operational efficiency optimization method for ship fleet to comply with the carbon intensity indicator (CII) regulation," *Ocean Eng.*, vol. 286, no. P1, p. 115487, 2026, doi: 10.1016/j.oceaneng.2023.115487.

[3] M. Barbri, M. Zimmermann, F. Dahms, and K. Müller, "Energy Conversion and Management : X Energy analysis of large cruise ships case study of thermal and electric demands and supply during different scenarios," *Energy Convers. Manag. X*, vol. 30, no. February, p. 101651, 2026, doi: 10.1016/j.ecmx.2026.101651.

[4] D. Li *et al.*, "Optimization of Thermal Environment in Cruise Ship Atriums Using CFD Simulation and Air Distribution Strategies," pp. 1–21, 2025.

[5] A. Brækken, C. Gabrielii, and N. Nord, "Energy use and energy efficiency in cruise ship hotel systems in a Nordic climate," *Energy Convers. Manag.*, vol. 288, no. April, p. 117121, 2023, doi: 10.1016/j.enconman.2023.117121.

[6] A. Ruvio, S. Elia, M. Pasquali, R. Pibiri, S. Mcphail, and M. Fontanella, "Innovative Power Generation System for Large Ships Based on Fuel Cells : A Technical – Economic Comparison with a Traditional System," pp. 1–22, 2025.

[7] A. Marashian, J. M. Böling, A. Razminia, and J. Hyvönen, "Combined engine configuration and speed optimization for fuel savings on cruise ships," *Ocean Eng.*, vol. 322, no. July 2024, p. 120387, 2025, doi: 10.1016/j.oceaneng.2025.120387.

[8] Y. Li *et al.*, "Leakage , diffusion and distribution characteristics of refrigerant in a limited space : A comprehensive review," *Therm. Sci. Eng. Prog.*, vol. 40, no. January, p. 101731, 2023, doi: 10.1016/j.tsep.2023.101731.

[9] F. Fabris, M. Fabrizio, S. Marinetti, A. Rossetti, and S. Minetto, "Evaluation of the carbon footprint of HFC and natural refrigerant transport refrigeration units from a life-cycle perspective," *Int. J. Refrig.*, vol. 159, no. December 2023, pp. 17–27, 2024, doi: 10.1016/j.ijrefrig.2023.12.018.

[10] J. Wajs, M. Mrozek, and E. Fornalik-wajs, "Combined cold supply system for ship application based on low GWP refrigerants - Thermo-economic and ecological analyses," *Energy Convers. Manag.*, vol. 258, no. December 2021, p. 115518, 2022, doi: 10.1016/j.enconman.2022.115518.

[11] Y. Yang and Z. Liu, "Analysis and optimization to cascade refrigeration system for building cold storage based on advanced exergy-based theory," *Energy Convers. Manag.*, vol. 342, no. January, p. 120128, 2025, doi: 10.1016/j.enconman.2025.120128.

[12] Y. Li, Y. Feng, C. Wang, Z. Xing, D. Ren, and L. Fu, "Performance evaluation and optimization of the cascade refrigeration system based on the digital twin model," *Appl. Therm. Eng.*, vol. 248, no. PA, p. 123160, 2024, doi: 10.1016/j.applthermaleng.2024.123160.

[13] P. Robinson, "Energy , exergy and environmental (3E) analysis of low GWP refrigerants in cascade refrigeration system for low temperature applications Analyse ´ mass flow rate ratio," *Int. J. Refrig.*, vol. 160, no. July 2023, pp. 373–389, 2024, doi: 10.1016/j.ijrefrig.2023.12.020.

[14] M. Arefin, D. Mondal, and A. Islam, "Energy Conversion and Management : X Optimizing cascade refrigeration systems with low GWP refrigerants for Low-Temperature Applications : A thermodynamic analysis," *Energy Convers. Manag. X*, vol. 24, no. July, p. 100722, 2024, doi: 10.1016/j.ecmx.2024.100722.

[15] S. Ji, Z. Liu, H. Pan, and X. Li, "Energy , exergy , environmental and exergoeconomic (4E) analysis of an ultra-low temperature cascade refrigeration system with environmental-friendly refrigerants," *Appl. Therm. Eng.*, vol. 248, no. PA, p. 123210, 2024, doi: 10.1016/j.applthermaleng.2024.123210.

[16] D. Staubach, B. Michel, and R. Revellin, "Refrigerant selection from an economic and TEWI analysis of cascade refrigeration systems in Europe based on annual weather data," *Appl. Therm. Eng.*, vol. 230, no. PB, p. 120747, 2023, doi: 10.1016/j.applthermaleng.2023.120747.

[17] P. Prajapati, V. Patel, B. D. Raja, and H. Jouhara, "optimization of a cascade refrigeration system," vol. 54, no. July, 2024.

[18] M. Yilmaz, C. Cimsit, A. Keven, and R. Karaali, "Case Studies in Thermal Engineering Analysis of cascade vapor compression refrigeration system using nanorefrigerants : Energy , exergy , and environmental (3E)," *Case Stud. Therm. Eng.*, vol. 57, no. April, p. 104373, 2024, doi: 10.1016/j.csite.2024.104373.

[19] O. Yılmaztürk, "Exergy Based Ecological Performance Analysis of a Waste Heat-Powered Marine Refrigeration Cycle," vol. 227, no. 1, pp. 34–42, 2025, doi: 10.54926/jnamt.2025.2410.

[20] L. Ventola *et al.*, "An experimental and forecast-driven Expanded Total Equivalent Warming Impact analysis of a water-to-water heat pump operated with R-1234yf-based fluids Air to Water Air to Water Heat Pump Energy Performance of Buildings Directive Referred to No Forecast Scenario Seasonal Coefficient of Performance," vol. 340, no. May, 2025, doi: 10.1016/j.enconman.2025.119969.

[21] W. Faruque, M. R. Uddin, S. Salehin, and M. M. Ehsan, "A Comprehensive Thermodynamic Assessment of Cascade Refrigeration System Utilizing Low GWP Hydrocarbon Refrigerants," *Int. J. Thermofluids*, vol. 15, no. July 2022, p. 100177, 2027, doi: 10.1016/j.ijft.2022.100177.

[22] J. Liu, Y. Gao, C. Lu, and M. Ahmad, "Enhancing energy and exergy performance of a cascaded refrigeration cycle : Optimization and comparative analysis LED," *J. Clean. Prod.*, vol. 438, no. August 2023, p. 140760, 2024, doi: 10.1016/j.jclepro.2024.140760.

[23] L. K. Cerveny, A. Miller, and S. Gende, "Sustainable cruise tourism in marine world heritage sites," *Sustain.*, vol. 12, no. 2, pp. 1–24, 2020, doi: 10.3390/su12020611.

[24] G. Barone, A. Buonomano, G. Del, G. Francesco, A. Palombo, and G. Russo, "Towards sustainable ships : Advancing energy efficiency of HVAC systems onboard through digital twin," *Energy*, vol. 317, no. December 2024, p. 134435, 2025, doi: 10.1016/j.energy.2025.134435.

[25] S. Asal, A. Acır, and I. Dincer, "A sustainable cruise ship development with cleaner production of electricity, heat, cooling, freshwater and hydrogen," *J. Clean. Prod.*, vol. 467, no. May, p. 142939, 2024, doi: 10.1016/j.jclepro.2024.142939.

[26] D. N. G. Patiluna, E. A. A. Donasco, N. M. Hernandez, J. B. A. Mamalias, and R. R. Viña, "Energy and exergy analysis of a two-stage cascade vapor compression refrigeration system with modified system configuration," *Int. J. Refrig.*, vol. 169, no. October 2024, pp. 33–54, 2025, doi: 10.1016/j.ijrefrig.2024.10.013.

[27] J. Wang, P. Gullo, and H. Ramezani, "Review on the trend of ultra-low-GWP working fluids for small-capacity vapour-compression systems," *Sustain. Energy Technol. Assessments*, vol. 66, no. March, p. 103803, 2024, doi: 10.1016/j.seta.2024.103803.

[28] M. Jeon, "Refrigeration System with Internal Heat Exchanger . Part 1 :," 2021.

[29] R. Llopis *et al.*, "TEWI analysis of a stand-alone refrigeration system using low-GWP fluids with leakage ratio consideration Analyse TEWI d ' un système frigorifique autonome utilisant des fluides à faible PRP prenant en compte le taux de fuite," *Int. J. Refrig.*, vol. 118, pp. 279–289, 2020, doi: 10.1016/j.ijrefrig.2020.05.028.

[30] E. Bellos, "applied sciences A Theoretical Comparative Study of CO 2 Cascade Refrigeration Systems," 2019, doi: 10.3390/app9040790.

[31] G. Shanmugasundar, K. Logesh, R. Cep, and R. Roy, "Evaluating Eco-Friendly Refrigerant Alternatives for Cascade Refrigeration Systems : A Thermoeconomic Analysis," 2023.

[32] S. Chaturvedi, N. K. Sharma, and C. Ranganayakulu, "Exergy analysis and performance evaluation of a vapor compression refrigeration system using R-134a , R-600a , and R-125," *Int. J. Refrig.*, vol. 175, no. October 2024, pp. 74–84, 2025, doi: 10.1016/j.ijrefrig.2025.03.034.

[33] J. Soni, V. Gupta, Y. Joshi, A. Upadhyay, R. Kumar, and S. Yadav, "Materials Today : Proceedings Investigative comparison of R134a , R290 , R600a and R152a refrigerants in conventional vapor compression refrigeration system," *Mater. Today Proc.*, no. June, 2023, doi: 10.1016/j.matpr.2023.07.286.

[34] M. Ghanbarpour, A. Mota-babiloni, B. E. Badran, and R. Khodabandeh, "applied sciences Energy , Exergy , and Environmental (3E) Analysis of Hydrocarbons as Low GWP Alternatives to R134a in Vapor Compression Refrigeration Configurations," 2021.

[35] Z. Dai, X. Chen, Q. Chen, X. Zhang, and H. Zhang, "Energy and exergy analysis of a novel two-stage ejector refrigeration cycle using binary zeotropic mixtures," *Int. J. Refrig.*, vol. 168, no. August, pp. 178–189, 2024, doi: 10.1016/j.ijrefrig.2024.08.016.

[36] S. Kumar, P. Gahlot, and S. Kumar, "Results in Engineering Energy , exergy and economical analysis of N 2 O based cascade refrigeration system for ultralow temperature cooling applications using different eco-friendly refrigerants in high temperature cycle," *Results Eng.*, vol. 22, no. April, p. 102259, 2024, doi: 10.1016/j.rineng.2024.102259.

[37] D. Nygeil *et al.*, "Energy and exergy analysis of a two-stage cascade vapor compression refrigeration system with modified system configuration Coefficient of Performance," vol. 169, no. August 2024, pp. 33–54, 2025, doi: 10.1016/j.ijrefrig.2024.10.013.

[38] L. V. S. Martins, C. H. M. Braga, J. J. G. Pabon, L. Machado, and W. M. Duarte, "Assessment of total equivalent warming impact (TEWI) of alternative refrigerants for retrofit of R22 in single split air conditioning system," *J. Build. Eng.*, vol. 88, no. December 2023, p. 109085, 2024, doi: 10.1016/j.jobe.2024.109085.

[39] A. Internal, H. Exchanger, P. Exergy, and M. Jeon, "Experimental Investigation of R404A Indirect Refrigeration System," 2024.

[40] A. F. Santos and P. D. Gaspar, "Ecoenergetic Comparison of HVAC Systems in Data Centers," pp. 1–13, 2021.

[41] F. Ceglia, E. Marrasso, C. Roselli, and M. Sasso, "An innovative environmental parameter : Expanded Total Equivalent Warming Impact," *Int. J. Refrig.*, vol. 131, no. May, pp. 980–989, 2021, doi: 10.1016/j.ijrefrig.2021.08.019.