Multidisciplinary
SCIENTIFIC JOURNAL
OF MARITIME RESEARCH

University of Rijeka
FACULTY OF MARITIME STUDIES

Multidisciplinarni
znanstveni časopis
POMORSTVO

https://doi.org/10.31217/p.37.2.7

The Comparative Analysis of Alternative Refrigerants on Ship Refrigeration Systems: Performance, Environmental, and Economic Approach

Yalcin Durmusoglu*, Gazi Kocak

Istanbul Technical University, Department of Marine Engineering, 34940, Tuzla, Istanbul, Turkiye, e-mail: ydurmusoglu@itu.edu.tr
* Corresponding author

ABSTRACT

The usage of CFC and HCFC gases, which are extensively used in ship refrigeration and air conditioning systems, has been restricted due to harmful effects on the ozone layer and global warming. Thus, the use of alternative refrigerants becomes a possible solution. In this study, the performance parameters, environmental and economic effects of the system for various refrigerants were analyzed comparatively for marine refrigeration systems. For this purpose, the refrigerants R407C, R1234yf, R245fa, R152a, R513a, R450a, R161, R453a, and R717 are investigated as alternatives to the most commonly used R22 and R134a refrigerants on board ships. The results show that the best alternatives -in terms of performance, environment and economy- for R22 are R717 (new) and R453A (drop-in) and for R134a are R717 (new) and R152a (drop-in). In addition, drop-in, retrofit or new system suitability of the analyzed refrigerants for replacement of R22 and R134a are presented.

ARTICLE INFO

Review article
Received 10 July 2023
Accepted 18 October 2023

Key words:
Ship refrigeration system
Alternative refrigerants
Environment
Performance
Total cost

1 Introduction

Environmental degradation and climate change are becoming more and more important problems day by day and regulations are being made for systems to work more efficiently. Due to its environmental effects, regulations regarding refrigeration and air conditioning systems are also made and updated. These rules and regulations are mostly to control the greenhouse gas emissions and ozone depleting gases on global scale. Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) are defined as the main indicators to determine the effect of refrigerants on the ozone layer and global warming. ODP is an index characterizing the participation of molecules in the depletion of the ozone layer. The value of this index is calculated by reference to a molecule that is, compared to R11 or R12 with an ODP of 1. The GWP index represents the contribution of a molecule to the greenhouse effect in 20, 100, 500 years by comparing it with the reference molecule CO_2 (Benzaoui and Benhadid-Dib, 2012).

The refrigerants can be divided into four categories as chlorofluorocarbons (CFC), hydrochlorofluorocarbons (HCFC), hydrofluorocarbons (HFC), and natural refrigerants. The natural refrigerants are carbon dioxide (R744), ammonia (R717), water (R718), air, and various hydrocarbons (HC). Among these fluids, CFCs are the most damaging to the ozone layer and have a high global warming potential. For this reason, some restrictions have been introduced around the world for the use of CFCs and the measures mentioned below have been taken. Although HCFCs react with the ozone layer due to the chlorine atom in their content, their chemical stability is very weak because they contain hydrogen in their structure. They cannot stay in the atmosphere for a long time without breaking their structure. Therefore, HCFCs have low ozone depletion potential. Since there is no chlorine atom in its structure, the ODP of HFCs is zero. However, they have a certain effect on global warming (Bulgurcu et al., 2007).

The Montreal Protocol was signed in 1987 by 43 nations with an aim of reducing production of CFCs to 50% by 1999. In addition, the parties to the Montreal Protocol decided on a phase-out schedule for all HCFCs by 2030 in 1992 (Balmer, 2011).

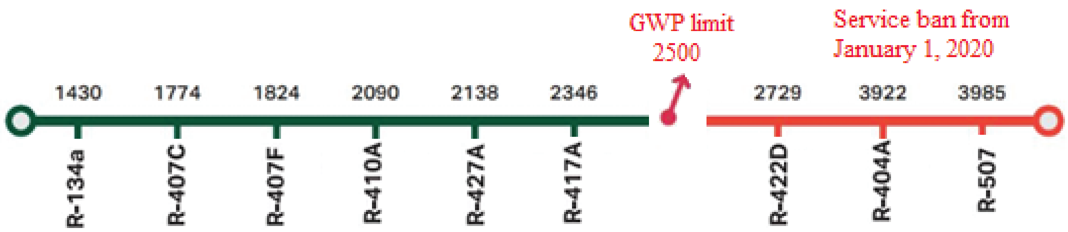

Figure 1 GWP Values of some of the HFCs

Source: Wilhelmsen Ship Service

There is a pressure to decrease the use of high-GWP refrigerants in various industries due to growing environmental concerns. Therefore, all 197 member countries, agreed to amend the Montreal Protocol in order to reduce hydrofluorocarbons (HFCs) gradually. The Kigali Amendment to the Montreal Protocol was approved on October 16, 2016, opening the door for the global phasedown of HFCs. According to this agreement, member countries are categorized according to their development status and are subject to different plans to reduce the use of HFCs to 15% of the amount in 2021 until 2045 (Kujak, 2017). Before the Kigali Agreement the U.S. Environmental Protection Agency (EPA) issued two rules regarding phase-out process of HFCs. The first rule determines the process for HFCs in retail food refrigeration, aerosols, propellants, and motor vehicles (EPA, 2015) and the second EPA rule determines the process for HFCs in chillers. According to second rule R-134a, R-410A and R-407C are forbidden in new chillers by Jan. 1, 2024 (EPA, 2016).

In EU countries, the F-gas Regulation (517/2014) went into effect on January 1, 2015, and it mandates a decrease in the use of HFCs as well as a total ban on HFCs with a high Global Warming Potential (GWP >2500), such as R-404A, R-507, and R-422D, by January 1, 2020. In the Figure 1 some of the HFC refrigerants with GWP values are shown. For non-EU flagged ships, new R-404A, R-507 and R-422D will still be available after 2020 (Wilhelmsen Ship Service, 2022).

The International Maritime Organization (IMO) is the primary regulating body for the maritime industry. The major convention for preventing pollution by ships is called MARPOL (International Convention for the Prevention of Maritime Pollution). Annex VI of MARPOL is for prevention of air pollution from ships and Regulation 12 is designated to the use of ozone depletion substances (ODS) in marine applications (IMO, 2005). According to this regulation on ships built on or after May 19, 2005, additional installations containing CFC or Halon are not allowed. Similarly, after January 1, 2020, new installations of HCFC equipment are prohibited on both new and existing ships (IMO, 2020).

Besides IMO, the classification societies have also important role on environmental issues and they propose voluntary class notations. For example DNV-GL offers two environmental class labels: "Clean" and "Clean Design" where label "Clean" means that the refrigerant can be HFC or natural refrigerants such as NH3 and CO_2. The label "Clean Design" means that the used refrigerants must be either natural refrigerant or HFC with a GWP of less than 2000 (Hafner et al., 2019). The the Registro Navale Italiano (RINA) limits the GWP of the refrigerants to a maximum of 2000 by CLEANAIR class notation (Registro Navale Italiano (RINA), 2014), Lloyd's Register (LR) limits the GWP of the refrigerants to a maximum of 1950 by ECO class notation (Lloyd's Naval Register, 2014), and the Bureau Veritas (BV) limits the GWP of the refrigerants to a maximum of 2000 by CLEAN-SHIP class notation (Bureau Veritas, 2014).

Ammar and Seddiek (2018) pointed out that 8.0% of the global CO_2 emissions are from ships which is shown in

Nomenclature

CFC Chlorofluorocarbons

COP Coefficient of Performance

EPA U.S. Environmental Protection Agency

EXV Expansion valve

GWP Global Warming Potential

HC Hyrocarbons

HCFC Hydrochlorofluorocarbons

HFC Hydrofluorocarbons

IMO International Maritime Organization

M Molecular mass

MARPOL International Convention for the Prevention of Maritime Pollution

ODP Ozone Depleting Potential

ODS Ozone Depletion Substances

T_{BP} Boiling Point (Temperature)

T_{CR} Critical Point Temperature

P_{CR} Critical Point Pressure

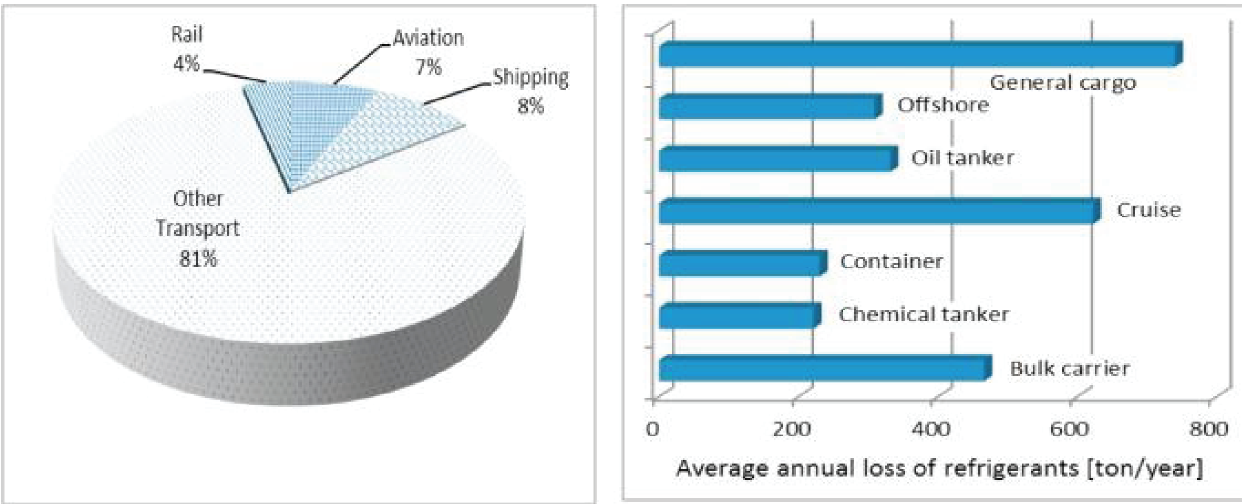

Figure 2 CO_2 and refrigerant emissions from ships

Source: Ammar and Seddiek, 2018.

Figure 2. It is estimated that CO_2 emissions from international shipping could grow by 50% to 250%, by 2050 (Peters et al., 2013 and Boden et al., 2013). Therefore, refrigeration and air conditioning systems on ships are one of the systems that should be examined in terms of energy efficiency, environmental and economic effects. The selection of refrigerant type is important for more efficient and environmentally friendly operation of the system.

R22 and R134a refrigerants usage is dominating the refrigeration preference in maritime sector. The world merchant fleet's total HCFCs/HFCs usage percentages are estimated as 70% for R22, 26% for R134a, and 4% for R404A (Glavan at al., 2022). The production and supply of R22 and R404A is prohibited by 2020 and the use of R134a in new systems is prohibited by 2024. Therefore, using refrigerants with low GWP and ODP values in cooling systems is important in the refrigeration industry. For this purpose, studies on the production and use of alternative fluids that are compatible with nature, not harmful to the ozone layer and not contributing to global warming have gained great importance and acceleration (Akdemir and Gungor, 2010).

2 Alternative Refrigeration Selection Process

When choosing a refrigerant, many parameters such as thermal capacity, efficiency, chemical properties (boiling point, critical point, etc.), availability and economy play a role (Almis et al., 2019). Due to 96% of refrigerants in maritime sector is R22 and R134a the refrigerant selection process is focused on these refrigerants.

2.1 Literature Review of R22 Replacement

Calm and Domanski (2004) studied the phase-out process of R22 and recommended R407C, R421A, R411A, R421B, R417A, R419A and refrigerants R407C, R410A, R407E, R410B for the new equipment [20]. Some of these refrigerants such as R410A are also listed in the controlled refrigerants as mentioned before. Besides, some of these refrigerants such as R421A, R421B, R419A have GWP values higher than 2500 which is also not preferable according to EU F-Gas regulation. Arora et al. (2007) compared the exergetic efficiency of R-22, R-407C and R-410A. The results of their study show that R22 performs superior to R407C and R410A. As an alternative to R22, R407 C is better than R410A for refrigeration purpose while R410 is better than R407C for air conditioning purpose. It is important to mention that R410A is one of the controlled refrigerants which will be prohibited at new systems by 2024. Jain et al. (2011) inspected R134a, R410A, R407C and M20 for the replacement of R22. They found that R407C performs better for replacement of R22 for existing systems with small retrofits. However, in the study of Siva et.al (2012) R134a outperforms R407C contrary to this study. Llopis et al. (2012) studied the drop-in and retrofit refrigerant alternatives for replacement of R22. They compared the performance parameters of R422A and R417B as drop-in fluids and R404A as retrofit fluid for a two-stage vapor compression system. All of the investigated refrigerants have GWP values over 3000 which is very high according to current regulations. Besides, the retrofit refrigerant R404A is already forbidden by 2020 as mentioned above. Yang and Wu (2013) investigated alternative refrigerants to R22. They analyzed refrigerants R744, R717, HC-290, RE170, HFC-32, HFC-161, HFC-152a, HFO-1234yf, HFO-1234ze (E) and evaluated technically. They claim that currently there is not a perfect refrigerant that can replace R22 in existing systems. They pointed out that pure HFO-1234yf and HFO-1234ze (E) were targeted as an alternative to R134a, thus not efficient alternative to HCFC-22. They found that for the coming 10 to 20 years

R410A, R407, R404A and some existing 'drop-in' blends seems the most feasible replacement solution of HCFC-22 in the developing countries. Then for the next decade's replacement with HFC-32, HCs, R744, and R717 will be feasible. They show that HCs,HFOs and HFC-161 has minimum impact on climate change. Sethi et al., (2015) investigated two potential alternatives to R22 which are HFC (R407C) and HFO based (R444B) for high ambient conditions. They resulted that R444B has superior properties comparing to R407C for the replacement of R22 for air conditioning applications which is mildly flammable. However, drop-in, retrofit or new system information is not mentioned for R44B. Besides it is known that R407C can replace R22 with small changes to system. Shen et al. (2016) studies the effect of microchannel heat exchangers to room air conditioners and made recommendations for replacement of R22 and R410A [26]. They compared the performance of R22, R410, R32, Propane, R-1234yf and R-1234ze. They found that microchannel heat exchangers enhance the performance only for refrigerants R-1234yf and R-1234ze. They recommend R32 for the replacement of R410 and R290 for the replacement of R22 for small size units. Bolaji et al., (2017) carried out the thermodynamic performance investigation of three very low GWP refrigerants for replacement of R22 in air conditioning systems which are R429A, R435A, and R457A. The thermophysical properties of these refrigerants found to be very similar to R22 with slightly higher performance values. However, there is no information about the replacement suitability of drop-in, retrofit or new equipment. Pramudantoro et al., (2018) investigated the performance changes due to drop-in replacement of R22 to R32 in domestic air conditioners. They carried out experiments for different charge amounts of R32 due to liquid density difference and found that 95% of R32 which corresponds to 77.9% of R22 is optimal. At this refrigerant charge mass, the cooling capacity and power input increased by 7.7% and 20% respectively. However, COP decreased by 12.1%. From the aspect of global warming the use of R32 will significantly reduce the emission. European Comission Report (2016) about F-Gas Regulation shows that R161 is an alternative to R22 but it is not used at commercial scale (EU, 2016). Kothale et al. (2016) carried out an experimental study about R161 as an alternative to various other refrigerants. They compared several parameters such as COP, discharge temperature, cooling capasity and power consumption. General finding of their study is showing that R161 has better COP, increased refrigeration effect, lower discharge temeperature, and higher compressor work. According to the experimental results, R161 has highest COP among the refrigerants R134a, R32, R410A, MR1. Considering replacement of R22, R161 has better cooling capacity than R290 and lower discharge temperature than R22. They concluded that it is possible to successfully suppress its inflammable nature as a mixture and it is a good alternative for replacement of high GWP refrigerants. Jog et al., (2018) studied R161 as an alternative to R22 and they found that R161 has increased refrigeration effect, lower discharge temperature and better COP [31]. They concluded that R161 is a promising refrigerant for replacement of R22 but the safety class of R161 is A3 and this should be taken into consideration. Utage et al., (2021) carried out an experimental study for replacement of R22 with R161. They used an existing 5.2 kW air conditioning system with R22 for experiments and used the low GWP drop-in refrigerants. They found that R161 exhibit similar properties to R22 and better in terms of energy efficiency. They also showed that the required charge for HFC-161 is only 55% of R22. Under drop-in test method, R161 has 3.4% lower cooling capacity than R22 but the energy consumption is reduced by 26,5%. And thus, the energy efficieny ratio (EER) of R161 is improved by 27.2% and it is proved to be an energy efficient and climate friendly alternative refrigerant. Al-Nadawi (2021) carried out an experimental study for replacement of R22 and they obtained that R134A and R407C are a good alternatives in terms of irreversibility analysis. Saengsikhiao and Taweekun (2022) analyzed various refrigerants for replacement of R22 and found that R438A can be one of the alternative fluids but it is not mentioned if it is suitable for drop-in, retrofit or new system. In this study another investigated refrigerant is R453A which has similar pressure values to R22 and have higher refrigeration effect and COP comparing to R22. Besides its GWP value is lower than R438A and it is suitable for drop-in replacement.

2.2 Literature Review of R134a Replacement

Siva et al., (2012) carried out the exergetic performance analysis and comparison of R134a, R143a, R152a, R404A, R407C, R410A, R502 and R507A. They found that R-134a has the highest performance whereas R407C is worse in performance. Their results proved that the environment friendly R-134a is the best refrigerant amongst selected refrigerants. Despite the authors claim that R134a is environment friendly it is one of the controlled refrigerants and it is forbidden in new systems by 2024. Another experimental study about R1234yf is carried out by Jarall (2012) for replacement of R134a at a refrigeration unit of a hermetic rotary compressor of 550 W. They did not make any change in the system components and oil. In the study the saturation temperature-saturation pressure curves of HFO-1234yf and R152a are similar to R134a. Even more, the pressure of R152a is less than the others which is actually preferable. However, HFO-1234yf is more popular than R152a due to the properties of less toxicity and flammability. The experimental results show that R1234yf has lower refrigeration effect and COP.

Kandoliya and Mehta (2016) studied the low GWP HFO refrigerants R-1234yf and R-1234ze and expressed that these refrigerants are expected to be the next generation refrigerants for mobile air conditioning and ejector refrigeration systems. The authors claim that R1234yf and R1234ze(E) can be used as drop-in replacements for R134a in small power systems.

Table 1 İnvestigated alternative refrigerants for marine refrigeration systems

Refrigerants	M (g.mol^{-1})	T_{BP} (°C)	T_{CR} (°C)	P_{CR} (MPa)	Replacements (Drop-in/Retrofit/New)	GWP	Price ($/kg)	Safety class
R22	86.5	-40.81	123.15	4.99	-	1700	11.2	A1
R161	48.06	-37.6	102.1	5.01	D	12	N/A	A3
R453A	88.80	-42.3	88.60	4.59	D	1765	59.63	A1
R407C	86.2	-43.63	86.14	4.639	R/N	1525	11.19	A1
R450A	75	-22	105.87	3.814	R/N	601	40.68	A1
R1234yf	114.04	-29.4	94.7	3.382	R/N	4	100	A2L
R245fa	134.05	15.05	153.86	3.65	R/N	1030	3.54	A2
R717	17.03	-33.3	132.3	11.42	N	0	1.49	B2L
R134a	102	-26.1	101.1	4.06	-	1300	12	A1
R152a	66.05	-24	113.3	4.76	D	120	10	A2
R450A	75	-22	105.87	3.814	D	601	40.68	A1
R513A	108.4	-27.9	97.51	3.67	D	629	41.78	A1
R1234yf	114.04	-29.4	94.7	3.382	D	4	100	A2L
R717	17.03	-33.3	132.3	11.42	N	0	1.49	B2L

Source: Author

Another study for replacement of R134a is carried out for cascaded refrigeration plants which is considering the low GWP refrigerant R152a for replacement (Cabello et al., 2017). They showed that performances of both refrigerants are similar and it is feasible to replace R134a as drop-in type.

Hmood et al., (2021) studied the replacement of R134a in domestic refrigeration and automobile air conditioning for drop-in and retrofit refrigerants. They found that R1234yf, R152a, R450A, and R513A are the most suitable refrigerants as R134a drop-in substitutes. Contrary to the study of Kondalina and Mehta (2016) they found that the pure R1234ze and its mixtures are not suitable drop-in replacements of R134a. But it is possible to replace R134A only in new systems. Besides, high flammability hydrocarbon refrigerants R290, R600, and R600a are alternatives to replace R134a with some modifications. Shaik et al. (2022) carried out the exergy and energy analysis of several low GWP refrigerants for the replacement of R134a in home refrigerators and found that R1234yf and R152a can be good drop-in alternatives. Gao et al., (2021) studied about the replacement situation of Chinese cold chain industry and show that it is slower than the air-conditioning industry. They point out that R717 and R744 are safe, environmentally friendly, and efficient alternatives which make it unassailable in the future for large- sized cold chain equipment. However, all the system should be renewed. They also show that R290 is promising alternative for small sized systems which is gaining momentum. Pigani et al., (2016) investigated replacement of R407f with low GWP refrigerants for passenger ships. They restricted the alternative refrigerants with null ODP value and maximum GWP of 150. They found that R717, R744, R1234yf, and R1234ze (E) are most promising low-GWP refrigerants for the marine refrigeration systems. They figured out that changing the current refrigeration systems to low-GWP refrigerants results in reduction in performance of system. Thus, they concluded that switching to low GWP refrigerants is not an effective strategy to diminish the total environmental impact.

In practical applications, especially due to the limitation of a used refrigerant, the most economically appropriate fluid is preferred. In systems that are not very old and are still usable, the use of fluids suitable for drop-in or retrofit is considered. Because a complete renewal of the system will incur a great cost. In new systems, a suitable system is selected depending on the refrigeration systems feature, capacity, initial investment costs and operational costs.

Since the most used refrigerants in ships are R22 and R134a, alternatives to these two fluids have been determined. The system suitability of alternative refrigerants for R22 and R134a are examined separately and shown in Table 1.

3 Material And Method

3.1 Investigated Ship Refrigeration System

An existing R22 based ship refrigeration system is taken as a reference system which is shown in Figure 3. This is a multi-evaporator vapor compression refrigeration system which consists of two evaporators. One of the evaporator is used as meat/fish store and the other is used as vegetable store. Generally, the meat store is kept at -18°C and the vegetable store is kept at +4°C. The expansion

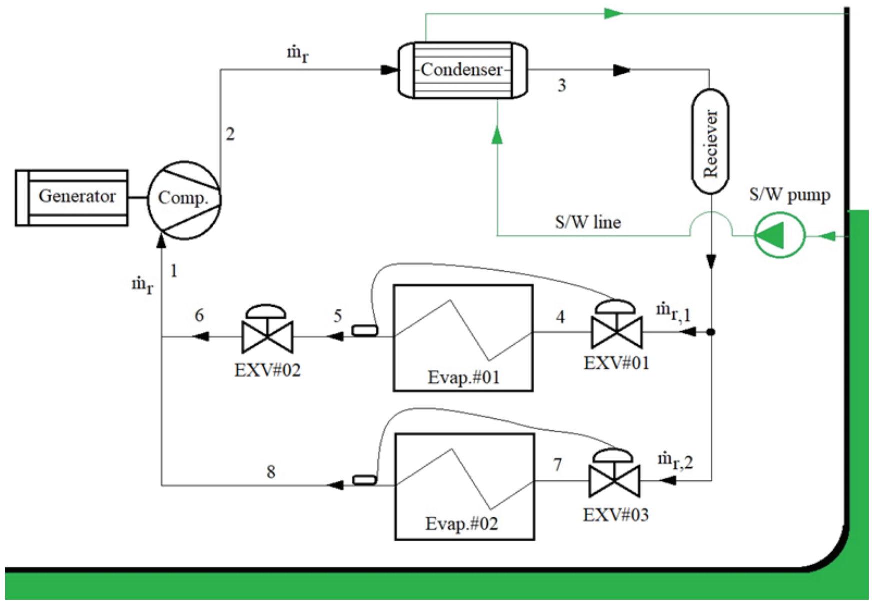

Figure 3 Investigated Ship Refrigeration System

Source: Author

valve-1 and expansion valve-3 are used for reducing the pressure to obtain necessary temperatures. And the expansion valve-2 is used to balance the output pressure of both evaporators. The operational parameters of the system are given in Table 2.

Table 2 Refrigeration system operating parameters

Components	Unit	Data
Power of compressor	kW	53 kW
Refrigerant	-	R22
Mass flow	kg/s	0.69
Operating hours[1]	h/yıl	3000
Cooling loads	kW	114
COP	-	2.15

[1] It is assummed that the regrigerator system is operated at 8 hour per day, 8 hour per day for deepfreeze and 8 hour per day for loadless.

Source: Author

3.2 Thermodynamic Model

Vapor compression refrigeration systems are continuous flow open systems. In the most general case, the 1st law of thermodynamics is expressed as:

$$\sum \dot{E}_{in} - \sum \dot{E}_{out} = \left(\frac{\Delta E}{dt}\right)_{system} \quad (1)$$

where $\dot{E}_{in}$ and $\dot{E}_{out}$ are inlet and outlet energy, respectively. The following expression is obtained by substituting the inlet and outlet energies, heat, work and mass energies in steady state condition from Equation 1.

$$\sum \dot{Q}_{net} + \sum \dot{W}_{net} + \sum \dot{m}_{in} e_{in} - \sum \dot{m}_{out} e_{out} = 0 \quad (2)$$

where $\dot{Q}$ is heat transfer to system or from system, $\dot{W}$ is power from system or to system. Here, e is the specific energy in kJ/kg and includes kinetic energy (ke), potential energy (pe), flow energy (pV) and internal energy (u). According to this specific energy is:

$$e = u + pv + ke + pe \left(\frac{\text{kJ}}{\text{kg}}\right). \quad (3)$$

Here, *u* is the internal energy, *pv* is the flow energy, *ke* is kinetic energy, and *pe* is the potential energy. While the terms *ke* and *pe* are neglected in continuous flow open systems, the internal energy and flow energy are combined as enthalpy ($h = u + pv$) and the most general case of the 1st law of thermodynamics can be simplified by substituting it in equation 2 which is expressed as follows.

$$\sum \dot{\mathrm{Q}}_{\mathrm{net}} + \sum \dot{\mathrm{W}}_{\mathrm{net}} + \sum \dot{\mathrm{m}}_{\mathrm{in}} \mathrm{h}_{\mathrm{in}} - \sum \dot{\mathrm{m}}_{\mathrm{out}} \mathrm{h}_{\mathrm{out}} = 0 \quad (4)$$

The expressions obtained by applying Equation 4 to each component of the system are summarized in Table 3. Finally, the coefficient of performance (COP) of the system is expressed as follows, taking into account that the system is double pressure.

$$\mathrm{COP} = \frac{\dot{\mathrm{Q}}_{\mathrm{eva,1}} + \dot{\mathrm{Q}}_{\mathrm{eva,2}}}{\dot{\mathrm{W}}_{\mathrm{comp}}} \quad (5)$$

where $Q_{eva,1}$ and $Q_{eva,2}$ indicates the heat transfer at provision store and refrigeration cargo hold, respectively, $\dot{W}_{comp}$ is power consumption of the compressor.

Table 3 Energy balances of refrigeration system components

Components	Equations (kW)	Equations
Compressor	$\dot{W}_k = \dot{m}_r(h_2 - h_1)$	Eq. (6)
Condenser	$\dot{Q}_c = \dot{m}_r(h_2 - h_3)$	Eq. (7)
	$\dot{Q}_c = \dot{m}_{sw}(h_{10} - h_9)$	Eq. (8)
Expansion Valve	$(h_4 = h_4)$ and $(h_6 = h_7)$	Eq. (9)
Evaporators	$\dot{Q}_{eva,1} = \dot{m}_{r,1}(h_5 - h_4)$	Eq. (10)
	$\dot{Q}_{eva,2} = \dot{m}_{r,2}(h_8 - h_7)$	Eq. (11)
COP	$(\dot{Q}_{eva,1} + \dot{Q}_{eva,2})/\dot{W}_c$	Eq. (12)

Source: Author

3.3 Economic Model

The annual total cost approach has been made for the economic cost analysis of the refrigeration system (De Paula et al., 2020). The total cost ($\dot{C}_T$) consists of the equipment annual initial investment costs of the refrigerant system ($\dot{Z}_i$), the annual operating cost of the system ($\dot{C}_{op}$), the annual environmental cost considering the CO_2 greenhouse gas effect ($\dot{C}_{env}$), and the annual refrigerant charging cost ($\dot{C}_{ref}$). Accordingly, the annual total cost is expressed by the following equation:

$$\dot{C}_T = \sum_i^n \dot{Z}_i + \dot{C}_{op} + \dot{C}_{env} + \dot{C}_{ref} \quad \left(\frac{\$}{\text{year}}\right) \tag{13}$$

3.3.1 Initial Investment Costs of Components

The initial investment cost of the components (Z_i) consists of the purchasing costs of all the components that make up the system. (Z_i) for the refrigeration system are calculated according to the following equations:

$$\sum_i^n Z_i = Z_{comp} + Z_{cond} + Z_{exv} + Z_{evap} \ (\$) \tag{14}$$

The initial investment cost equations of each component are shown in Table 4.

Table 4 Initial investment cost equations of each component

Components	Investment cost equations	Auxiliary equations	Equations
Compressor	$Z_{comp} = 39.5\frac{\dot{m}_{ref} P_r Ln(P_r)}{(0.9 - \eta_{comp})}$	$P_r = \frac{P_2}{P_1}$	Eq. (15)
Condenser	$Z_{cond} = 516.62(A_{cond}) + 268.4$	$A_{cond} = \frac{\dot{Q}_{cond}}{U_{cond}.\Delta T_{LMT}}$	Eq. (16)
Expansion Valves	$Z_{exp} = 114.6\dot{m}_{ref}$	---	Eq. (17)
Evaporators	$Z_{evap} = 516.62(A_{evap}) + 268.4$	$A_{evap} = \frac{\dot{Q}_{evap}}{U_{evap}.\Delta T_{LMT}}$	Eq. (18)

Source: De Paula et al., (2020)

Here η_{comp} is the isentropic efficiency of the compressor and 0.87 is accepted in this study. In order to calculate the annual value of the initial investment costs of the components, the investment discount rate value must be calculated. Investment discount rate is expressed as:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}. \quad (19)$$

The equation including the annual initial investment costs of the components, the maintenance-repair coefficient φ, is obtained as follows:

$$\sum_i^n \dot{Z}_i = (Z_{comp} + Z_{cond} + Z_{exv} + Z_{evap})\varphi CRF. \quad (20)$$

3.3.2 Operating Cost of the System

The operating cost, C_{op}, varies depending on the power consumed by the compressor in the system ($\dot{W}_{comp}$), the annual operating time of the system (H_{oper}), the specific fuel consumption (*sfoc*) of the generators for the power required for the compressor, and the unit fuel price (c_{fuel}). Accordingly, the annual operating cost equation is expressed as:

$$\dot{C}_{op} = \dot{W}_{comp} H_{oper} C_{elec} \quad (21)$$

$$\mathrm{H_{oper}} = (365).\,\mathrm{t_{day}} \quad (22)$$

$$C_{elec} = sfoc\left(\frac{c_{fuel}}{1000}\right) \quad (23)$$

Here, the daily operating time t_{day} is given as daily working hours of compressor (*h/day*).

3.3.3 Refrigerant Charging Costs

There is a charging cost for alternative refrigerants to be used in the system. Although the market prices of each refrigerant vary, calculations are made based on unit mass sales prices shown in Table 1. In this section, the amount of recharging due to leakages in the system is not taken into account. The equation that gives the purchase cost of the refrigerant supplied to the system is as follows:

$$\dot{C}_{ref} = m_{ref} c_{ref} \mathrm{CRF}. \quad (24)$$

Here, $\dot{C}_{ref}$ and c_{ref} are the annual total cost of the refrigerant ($/year) and the unit cost of the refrigerant ($/kg), respectively. The m_{ref} in Equation (24) represents the mass of the refrigerant in kg. Refrigerants are generally sold in about 10 kg tubes.

3.3.4 Environmental Cost

In the environmental model, only CO_2 is taken into account, one of the greenhouse gases that affect global climate change. Alternative refrigerants directly affect the compressor energies in the systems. The electrical energy of the compressors on the ships is provided by diesel generators by consuming fossil (MGO) fuel. In the case of the use of alternative refrigerants, the change in compressor work will affect the fuel consumed in the generator and therefore the combustion product CO_2 gas released into the atmosphere. The increase or decrease in energy consumption of compressors due to alternative gases will be equal to the energy drawn from the generator. Since it is assumed that generators release 3.179 kg of CO_2 gas for an average of 1 kWh energy production (Entec, 2022), the environmental impact of the annual energy consumption of the system is calculated as follows:

$$\dot{m}_{CO2} = \dot{m}_{fuel} ef_{CO2} \quad (25)$$

$$\dot{C}_{env} = \dot{m}_{CO2} C_{CO2}'\,dir. \quad (26)$$

Here ef_{CO_2} is emission factor which is expressed as $\left(\frac{kg_{CO_2}}{kg_{fuel}}\right)$ (Entec, 2002).

The assumptions made in both thermodynamic and economic performance calculations and their values are given in Table 5.

Table 5 Economical and environmental assumptions

Parameter	Value	Units	Comments
sfoc	0.285	kg/kWh	Specific fuel consumption of generator
t_{day}	8	h/day	Annual operating time of refrigeration system
c_{fuel}	803	$/Mton	(MGO) unit price[1]
ef_{CO2}	3.179	kg_{CO2}/t_{fuel}	CO_2 emission factor[2]
C_{CO2}	0.09	$/$kg_{CO2}$	Unit kg_{CO2} tax price
i	%14	-	Interest rate
n	20	year	Lifetime of system
φ	1.06	-	Maintenance cost coefficient
U_{evap}	0.03	kW/m²K	Total heat transfer coefficient
U_{cond}	0.04	kW/m²K	Total heat transfer coefficient
T_{eva1}	5	°C	Evaporator temperature of vegetable room
T_{eva2}	-24	°C	Evaporator temperature of meat room
η_{comp}	0.87	-	Compressor efficiency

Source: World bunker prices, 2023[1]; ENTEC, 2002[2]

4 Results and Discussion

The current ship refrigeration system's performance model was developed with the engineering equation solver (EES) software. The software is used for the calculations of the performance, economic and environmental analyzes of the determined alternative refrigerants for R22 and R134a refrigerants and then the results are discussed.

4.1 Thermodynamic Performance Results

In the inspected ship refrigeration system R22 is used as refrigerant. The determined alternative refrigerants for R22 are R717, R453a, R245fa, R161, R1234yf and R407C gases. The COP of the system using R22 is calculated as 3.063. The performance values of alternative refrigerants determined for the existing refrigeration system are R717 (COP=3.702), R453A (COP=3.344), R245fa (COP=3.336), R161 (COP=3.116), R1234yf (COP=3.022), and R407C (COP= 2.629), respectively. We can compare these values in Figure 4. Here, while the highest COP value is reached with R717 refrigerant, it should be considered that this fluid is suitable for the new system. For existing systems, the highest performance value is achieved with R453A fluid.

Alternative refrigerants determined for R134a refrigerant are R152a, R513a, R450a, and R1234yf. The performance value of the current refrigeration system with R134a is calculated as 3.344. The performances of selected alternative gases are calculated as R717 (COP=3.702), R152a (COP=3.196), R513a (COP=3.052), R450a (COP=3.051), and R1234yf (COP=3.022), respectively (Figure 5).

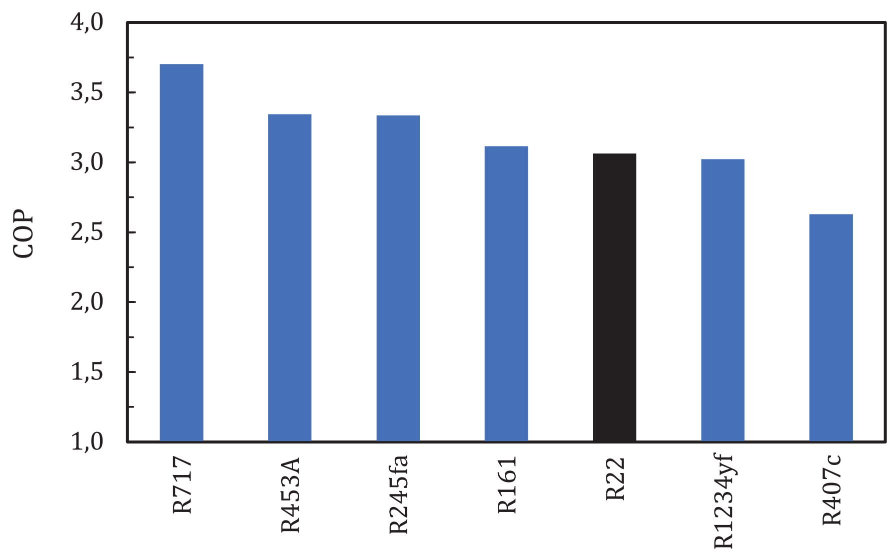

Figure 4 Coefficient of performance for alternative refrigerants to R22

Source: Author

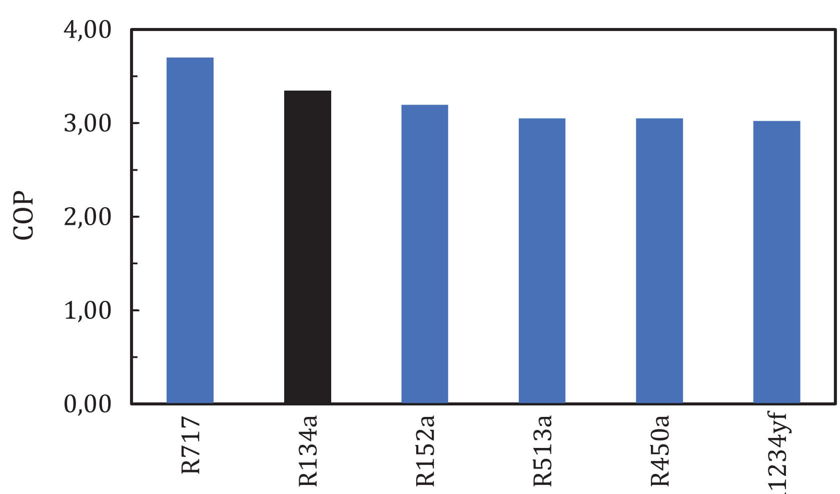

Figure 5 Coefficient of performance for alternative refrigerants to R134a

Source: Author

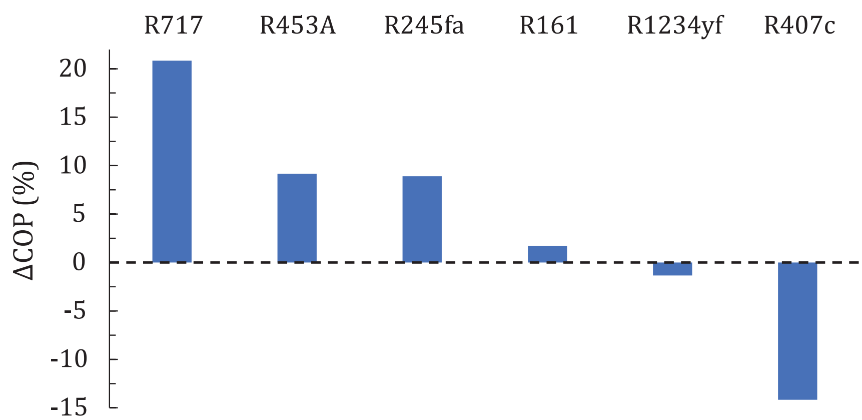

Figure 6 Change of COP for R22 alternative refrigerants

Source: Author

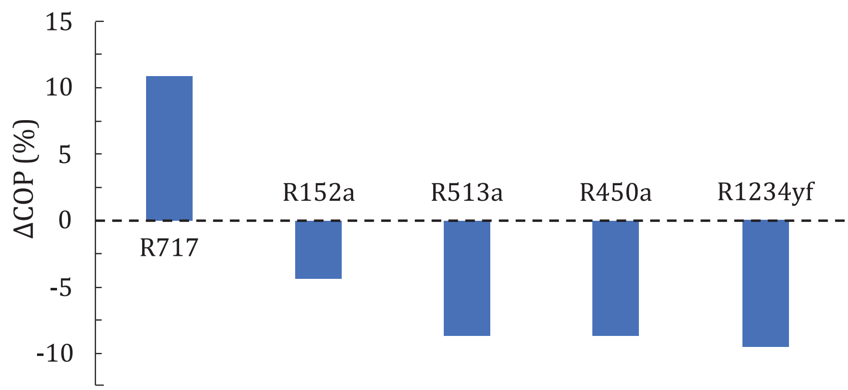

Figure 7 Change of COP for R134a alternative refrigerants

Source: Author

In Figure 6, the change of COP values of alternative refrigerants comparing to R22 are displayed. The best performance increase against R22 gas is obtained with R717 gas. Compared to the current situation, the change has increased by 20.86%. While other alternative refrigerants R453, R245fa, R161 provide 9.17%, 8.91% and 1.73% increase, respectively. Besides, R1234yf and R 407C cause a 1.34% and 14.2% decrease in the current system's performance, respectively.

Figure 7 shows the change of COP values of alternative refrigerants comparing to R134a. Except for R 717 all of the other alternative refrigerants cause performance losses. R717 result in 10.7% increase in performance in which the system should be renewed. The greatest loss was observed in R12354yf gas with a rate of 9.63%. Loss rates of other gases are 4.43% in R152a gas, 8.73% in R513a gas, and 8.76% in R450a gas.

4.2 Environmental Results

In this section, the annual CO_2 gas that is indirectly released to the atmosphere from the refrigeration system is taken into account. Any alternative refrigerants considered to be used in the current system cause increases or decreases in compressor power consumption. The electrical energy needed by the compressor on ships is provided by diesel generators. Generators consuming Marine Gas Oil (MGO) have to spend more or less fuel depending on the amount of increase or decrease in compressor energy. While calculating CO_2, the amount of fuel consumed for the energy of the compressor in the generator is taken as a basis. The CO_2 gas released to the atmosphere as a result of the combustion of the fuel consumed here has been calculated in $kgCO_2$ annually according to equation (25). The obtained results are shown in Figure 8.

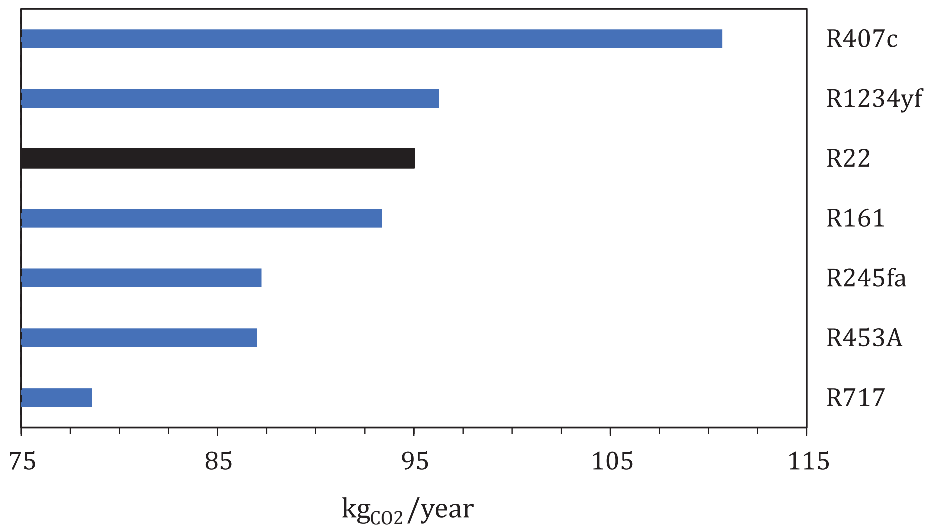

Figure 8 CO_2 gas released to the atmosphere by refrigerants as an alternative to R22 gas

Source: Author

The amount of CO_2 gas emission originating from the R22 gas used in the current system has been obtained as 95 kg per year. R717, which is an alternative to R22, draws attention as the gas that releases the least CO_2 gas to the environment. With the use of this refrigerant, the amount of CO_2 gas released from the generators to the atmosphere is 78.62 kg per year. The amounts of CO_2 release to the atmosphere due to other refrigerants are as follows: 96.28 kg from R1234yf, 93.38 kg from R161, 87.23 kg from R245fa, 87.02 kg from R453A and 110.7 kg from R407C. Here, it is observed that the refrigerant that causes the most CO_2 gas emission is R407C, while R1234yf also causes more CO_2 emission than R22.

In Figure 9, the changes in the CO_2 emission rate of other fluids compared to the R22 refrigerant are shown in percent. The refrigerants cause a decrease in CO_2 emissions are R717 by 17.25%, R453A by 8.41%, R245fa by 8.19% and R161 by 1.72%. On the other hand, R1234yf cause increase of CO_2 release by %1.37 and R407C is the worst case by %16.51.

R134a draws attention as the refrigerant that releases the least amount of CO_2 to the atmosphere in kg annually in the current system comparing to drop-in and retrofit alternatives. However, R717 shows a much better environmental performance. In Figure 10, the amount of CO_2 gas emission originating from the R134a gas used in the cur-

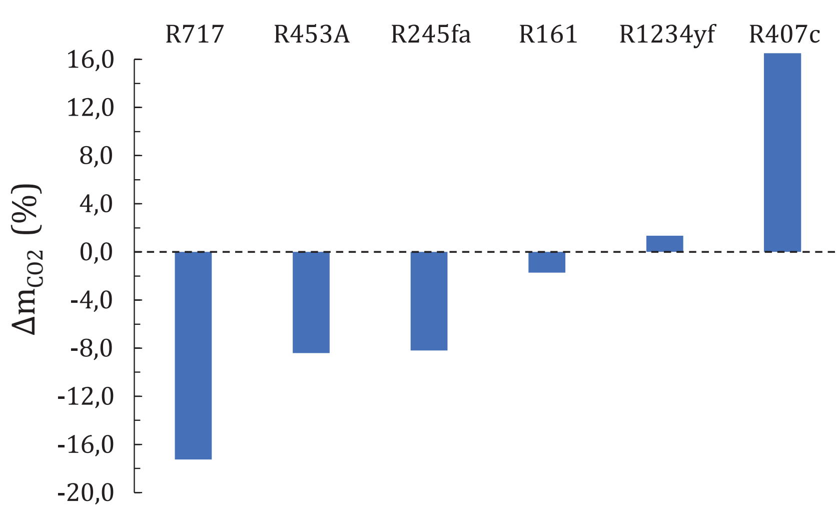

Figure 9 Changes in CO_2 emission rate of alternative refrigerants compared to R22

Source: Author

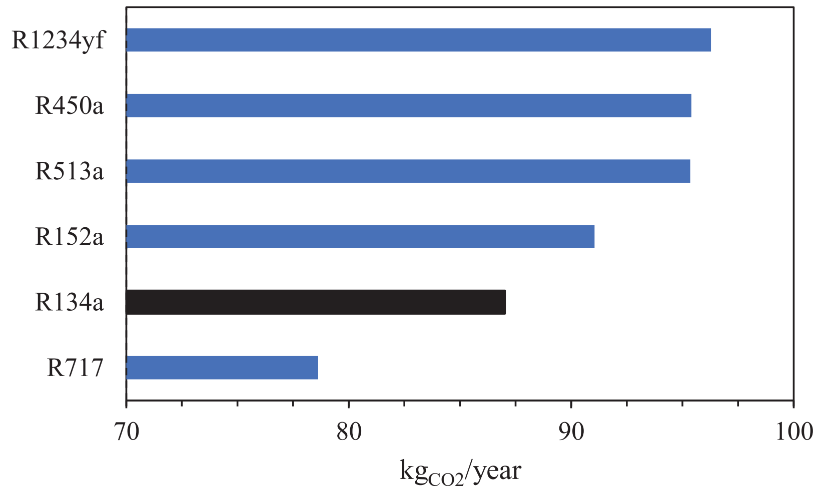

Figure 10 CO_2 gas released into the atmosphere by refrigerants as an alternative to R134a gas

Source: Author

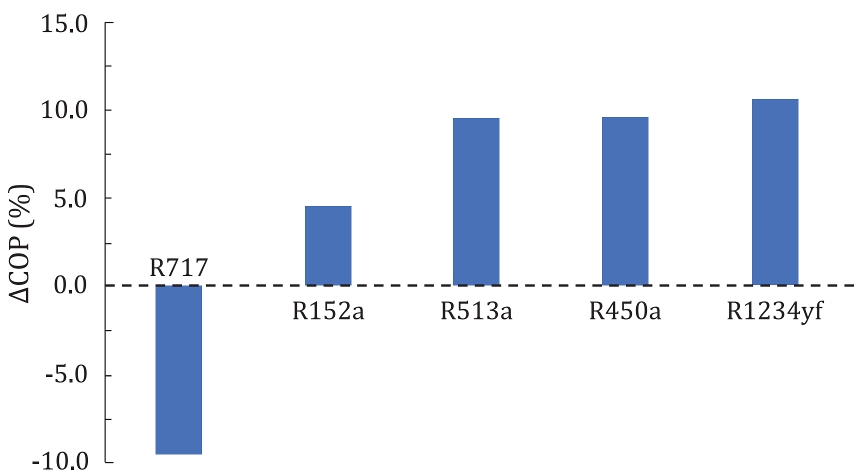

Figure 11 CO_2 emission rates of alternative refrigerants compared to R134a gas

Source: Author

rent system is calculated as 87 kg per year. All of the alternative gases release more CO_2 into the atmosphere than R134a except for R717. These values are calculated as 78.62 kg for R717, 98.28 kg for R1234yf, 95.4 kg for R450A, 95.35 kg for R513a and 91.05 kg for R152a, respectively.

Annual CO_2 emission rates of alternative refrigerants comparing to R134a are given in Figure 11. Accordingly, the annual CO_2 increase rates of refrigerants are R717 by -9.65, R1234yf by 10.64%, R450A by 9.63%, R513a by 9.57% and R152a by 4.63% compared to R134a.

4.3 Economical Results

Annual total cost approach was used for cost analysis. In the calculations, using Equations (13-26), the total costs of R22 and R134a gases are calculated as \$86875 and \$94488, respectively. The effects of the use of alternative refrigerants on the total cost of the system are shown in Table 6 separately for to R22 and R134a.

The results show that the total cost of R717, which is the best alternative to R22, is the lowest with \$75683, while the refrigerant with the highest cost is R1234yf with \$108949. Apart from these, the total costs of R453A, R245fa and R161 gases are \$98244, \$102196 and \$86251, respectively. The changes in the total cost of these gases comparing to R22 in the increasing or decreasing direction are calculated as R717 by -12.88%, R453A by 13.09%, R245fa by 17.64% and R161 by -0.72%.

For alternatives to R134a refrigerant, the lowest total cost is calculated for R717 which is \$75683 and corresponding to -19.90% decrement. R152 is second better re-

Table 6 Total cost of system for alternative refrigerants

for R22	C_T ($.year^{-1})	ΔC_T (%)	for R134a	C_T ($.year^{-1})	ΔC_T (%)
R22	$86875	-	**R134a**	$94488	-
R717	$75683	-12.88	**R717**	$75683	-19.90
R453A	$98244	13.09	**R152a**	$87579	-7.31
R245fa	$102196	17.64	**R513a**	$101359	7.27
R161	$86251	-0.72	**R450a**	$99891	5.72
R1234yf	$108949	25.41	**R1234yf**	$108949	15.30
R407c	$93621	-0.92			

Source: Author

frigerant which is $87579 and corresponding to decrement of -7.31% as a drop-in alternative. The total cost of R407C is $93621 by a decrement of -0.92%. For other alternative refrigerants the calculations are $99891 by 5.72% increment for R450a and $101359 by 7.27% increment for R513a. The highest increase is observed for R1234yf which is $108949 and corresponds to 15.30% increase of total cost.

In this study, alternative refrigerants were investigated for replacement of progressively phased out R22 and R134a refrigerants, which are most widely used in ship refrigeration systems. In terms of selection criteria, drop-in, retrofit or new system were taken into consideration. As an alternative to R22 gas, R717, R453A, R245fa, R161, R1234yf, and R407C gases were investigated while R717, R152a, R513a, R450A, and R1234yf gases were investigated as alternatives to R134a. The effects of the selected alternative gases on thermodynamic performance of the system, the CO_2 gas emission and the total cost of the system were examined comparatively. The following results are figured out from the analysis.

The evaluation for the refrigerants alternative to R22:

i. In systems with R22 refrigerant, the best COP value was obtained in R717 with 3.702, and the worst COP value was obtained in R407C with 2.629 in terms of system performance. When using R717 refrigerant, a 20.862 percent increase in system performance was observed compared to R22. However, the system needs to be renewed for R717 refrigerant. In addition, the best performance in drop-in alternatives is calculated as 3,344 with the R453.

ii. In terms of environmental impact, the refrigerant that causes the least CO_2 release is R717, and the refrigerant that causes the most CO_2 release is R407C. While R717 releases 78.62 kg of CO_2 into the atmosphere annually, R407C refrigerant releases 110.7 kg of CO_2 annually. In other words, while there is a 17.25% decrease in the CO_2 gas emissions released into the atmosphere with R717 gas, the CO_2 emission rate with R407C causes an increase by 16.51%. When the drop-in alternative R453A is used, CO_2 release is reduced by 8.41%.

iii. In the evaluation made in terms of annual total cost, for the replacement of R22 refrigerant, the alternative refrigerant with the lowest total cost value was calculated as R717, and the refrigerant with the highest total cost value was calculated as R1234yf. While the system with R717 refrigerant requires 12.883% less investment compared to the existing system, the system with R1234yf refrigerant requires 25.41% more investment. With the drop-in alternative R453A, an increase of 13% was observed in the total investment cost.

The evaluation for the refrigerants alternative to R134a:

i. The COP values of all drop-in and retrofit alternatives in terms of thermodynamic performance have been determined to be lower than R134a. R152A refrigerant gives the closest result to the current system in terms of performance. Accordingly, R152A causes a decrease of 4.43% in performance with a COP value of 3.196. Performance losses due to usage of other alternative refrigerants vary between 8.73% and 9.63%. R717 is the only alternative performs better than R134a with 3.7 COP value which corresponds to 10.7% increase in thermodynamic performance.

ii. Compared to R134a gas, annual CO_2 emission rates to the atmosphere by drop-in and retrofit alternative refrigerants show an increase starting from 4.63% to 10.64%. The annual amount of CO_2 gas released to the atmosphere by the R152a alternative refrigerant, which gives the closest result in terms of performance, is 91 kg. As a new system alternative R717 is less than R134a which is 78.62 kg and corresponding to decrease of -9.65%.

iii. R717 is the best alternative with $75683 total cost which corresponds to decrease of -19.9%. However, the system renewal is necessary. As a drop in alternative R152a refrigerant, which has lower performance and environmental impact than R134a, gave a better result in terms of total cost. It provides a savings of approximately $6900 in total annual cost. Thus, the R152a refrigerant system provides an annual savings of 7.312% in terms of total cost. Other alternatives increase from 7.31% to 15.31% in annual total cost compared to R134a.

5 Conclusion

Considering the progressive phase out process until 2050, it is deemed appropriate to use R717 in new systems as an alternative to R22 refrigerant, and to replace existing systems with R453A in terms of performance, environmental impact and total cost. For R134a refrigerant replacement, the results show that R717 is better in all terms except for the necessity of system renewal. It is observed that the drop-in alternative R152a refrigerant is better than other alternatives in terms of performance, environmental impact and cost. It seems as a suitable strategy to continue using R134a until it is completely banned and then switch to R152a refrigerant. For the new systems or in the necessity of system renewal R717 is one of the best alternatives.

Funding: Not applicable

Availability of data and material: open data access.

Author Contribution Statement: Yalcin Durmusoglu: Methodology, Software, Visualization. Gazi Kocak: Conceptualization, Writing – Original draft preparation, Investigation.

Conflicts of interest/Competing interests: Not applicable

References

[1] Benzaoui, A., Benhadid-Dib, S. (2012) Refrigerants and their environmental impact substitution of hydro chlorofluorocarbon HCFC and HFC hydro fluorocarbon. Search for an adequate refrigerant. Energy Procedia, 18, 807-816. doi: 10.10162012.05.096.

[2] Bulgurcu, H., İlten, N., Kon, O. (2007) Soğutucu Akışkanların Çevresel Etkileri ile İlgili Yeni Yasal Düzenlemeler ve Hedefler. *Ulusal Tesisat Mühendisliği Kongresi*, 8, 915-928.

[3] Balmer, R. T. (2011) Modern Engineering Thermodynamics. Elsevier Pub.

[4] Kujak, S. (2017). Flammability and new refrigerant options. *ASHRAE Journal*, *59*(5), 16-23.

[5] EPA. 2015. "Protection of Stratospheric ozone: change of listing status for certain substitutes under the Significant New Alternatives Policy Program; Final Rule" *Federal Register* 80(138):42870-42959. U.S. Environmental Protection Agency.

[6] EPA. 2016. "Protection of Stratospheric Ozone: new listings of substitutes; changes of listing status; and reinterpretation of unacceptability for closed cell foam products under the Significant New Alternatives Policy Program; and revision of Clean Air Act Section 608 Venting Prohibition for Propane; Final Rule." *Federal Register* 81(231):86778-86895. U.S. Environmental Protection Agency.

[7] Wilhemsen Ship Service (2022). [Online]. https://www.wilhelmsen.com/ships-service/refrigeration-solutions/EU-F-gas-Regulation-What-it-means-for-the-Maritime-Industry/ [Accessed 22 August 2022].

[8] International Maritime Organization (IMO). [Online]. https://www.imo.org/ en/ourwork/ environment/pages/ air-pollution.aspx. [Accessed 01 September 2022].

[9] International Maritime Organization (IMO). [Online]. https://www.imo.org/en/ OurWork/ Environment/Pages/ Index-of-MEPC-Resolutions-and-Guidelines-related-to-MARPOL-Annex-VI.aspx. [Accessed 01 September 2022].

[10] Hafner, A., Gabrielii, C. H., Widell, K. (2019) Refrigeration units in marine vessels: Alternatives to HCFCs and high GWP HFCs, Nordisk Ministerråd, Copenhagen. Available from: http://dx.doi.org/10.6027/TN2019-527.

[11] Registro Navale Italiano (RINA), 2014. Rules for the classification of ships.

[12] Lloyd's Naval Register, 2014. Rules and regulations for the classification of ships.

[13] Bureau Veritas, 2014. Rules for the classification of steel ships.

[14] Ammar, N. R., and Seddiek, I. S. (2018). Thermodynamic, environmental and economic analysis of absorption air conditioning unit for emissions reduction onboard passenger ships. *Transportation Research Part D: Transport and Environment*, *62*, 726-738.

[15] Peters, G. P., Andrew, R. M., Boden, T., Canadell, J. G., Ciais, P., Le Quéré, C., & Wilson, C. (2013). The challenge to keep global warming below 2 C. *Nature Climate Change*, *3*(1), 4-6.

[16] Boden, T.A., Andres, R.J., Marland, G. (2013). Global, Regional, and National Fossil-Fuel CO_2 Emissions, Period of Record 1751–2010. Carbon Dioxide Information Analysis Center (CDIA C), U.S. Department of Energy.

[17] Glavan, I., Poljak, I., Mustać, M., & Lonić, I. (2022). Natural Refrigerant on Board Marine Vessels. *Pomorski zbornik*, *62*(1), 43-56.

[18] Akdemir, Ö., Güngör, A. (2010). Maximum Performance Analysis for CO_2 Refrigeration Cycles. *Journal of Thermal Science and Technology*, 30(2), 37-43.

[19] Almış, Ç., Altıntaş, A., İyim, E., Karbondioksit Akışkanlı Transkritik Soğutma Sistemlerinde Valf Seçim Kriterleri. *14. Ulusal Tesisat Mühendisliği Kongresi*, 487-986. 2019.

[20] Calm, J. M., & Domanski, P. (2004). R-22 replacement status. *ASHRAE journal*, *46*, 29-39.

[21] Arora, A., Arora, B. B., Pathak, B. D., & Sachdev, H. L. (2007). Exergy analysis of a vapour compression refrigeration system with R-22, R-407C and R-410A. *International journal of Exergy*, *4*(4), 441-454.

[22] Jain, V., Kachhwaha, S. S., & Mishra, R. S. (2011). Comparative performance study of vapour compression refrigeration system with R22/R134a/R410A/R407C/M20. International journal of energy and environment, 2(2), 297-310.

[23] Llopis, R., Torrella, E., Cabello, R., & Sánchez, D. (2012). HCFC-22 replacement with drop-in and retrofit HFC refrigerants in a two-stage refrigeration plant for low temperature. *International journal of refrigeration*, *35*(4), 810-816.

[24] Yang, Z., & Wu, X. (2013). Retrofits and options for the alternatives to HCFC-22. *Energy*, *59*, 1-21.

[25] Sethi, A., Becerra, E. V., Motta, S. F. Y., & Spatz, M. W. (2015). Low GWP R22 replacement for air conditioning in high ambient conditions. *International journal of Refrigeration*, *57*, 26-34.

[26] Shen, B., Bhandari, M., Rane, M., & Mota, D. (2016). Low GWP refrigerants modelling study for a room air conditioner having microchannel heat exchangers, *International Refrigeration and Air Conditioning Conference*. Paper 1796. http://docs.lib.purdue.edu/iracc/1796.

[27] Bolaji, B. O., Oyelaran, O. A., & Okoye, O. C. (2017). Thermodynamic study of environment-friendly R429A, R435A and R457A refrigerants as substitutes for ozone depleting R22 in refrigeration and air-conditioning systems. *Pomorstvo*, *31*(1), 45-52.

[28] Pramudantoro, T. P., Sukamto, E., Sumeru, K., Margana, A. S., & Sukri, M. F. (2018, August). Effect of refrigerant charge variation of R32 as drop-in replacement for R22 in air conditioning system. In *AIP Conference Proceedings* (Vol. 2001, No. 1, p. 020009). AIP Publishing LLC.

[29] European Comission Report, (2016) Information for importers of equipment containing fluorinated greenhouse gases on their obligations under the EU F-gas Regulation.

[30] Kothale, K., Mali, K. V., Nimbalkar, S. D. (2016). Study of R-161 refrigerant as an alternate refrigerant to various other refrigerants. *International Journal of Current Engineering and Technology*, *4*(4), 236-241.

[31] Jog, R, Mali, K.V., Ladkat, R, Bhojane, P, Ahire, R, Utage, A. (2018). HFC-161 as an alternative to HCFC-22 in Air Conditioner. *International Journal for Research in Engineering Application & Management (IJREAM),* Special Issue, AMET 2018.

[32] Utage, A. S., Mali, K. V., & Phadake, H. C. (2021). Performance simulation of HFC-161 as an alternative refrigerant to HCFC-22 for room air conditioner. *Materials Today: Proceedings*, *47*, 5594-5597.

[33] Al-Nadawi, A. K. (2021). Irreversibility analysis of R407C, R404A, and R134A as an alternatives of R22 in vapor compression chiller under cycling conditions. *International Journal of Thermodynamics*, *24*(1), 24-29.

[34] Saengsikhiao, P., & Taweekun, J. (2022). Investigation and Analysis of R438A as an Alternative Refrigerant to R22 with Lower Global Warming Potential. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, *95*(1), 164-187.

[35] Siva Reddy, V., Panwar, N. L., & Kaushik, S. C. (2012). Exergetic analysis of a vapour compression refrigeration system with R134a, R143a, R152a, R404A, R407C, R410A, R502 and R507A. *Clean Technologies and Environmental Policy*, *14*, 47-53.

[36] Jarall, S. (2012). Study of refrigeration system with HFO-1234yf as a working fluid. I*nternational journal of refrigeration*, *35*(6), 1668-1677.

[37] Kandoliya, P. D., & Mehta, N. C. (2016). A recent review of refrigerant R-1234yf and R-1234ze (E). *Int J Emerging Tech and Innov Res*, *3*, 59-64.

[38] Cabello, R., Sánchez, D., Llopis, R., Catalán, J., Nebot-Andrés, L., & Torrella, E. (2017). Energy evaluation of R152a as drop in replacement for R134a in cascade refrigeration plants. *Applied Thermal Engineering*, *110*, 972-984.

[39] Hmood, K. S., Apostol, V., Horatiu, P. O. P., Badescu, V., & Elena, P. O. P. (2021). Drop-in and retrofit refrigerants as replacement possibilities of R134a in domestic/commercial refrigeration and automobile air conditioner applications. *Journal of Thermal Engineering*, *7*(7), 1815-1835.

[40] Shaik, M. H., Kolla, S., & Prasad Katuru, B. (2022). Exergy and energy analysis of low GWP refrigerants in the perspective of replacement of HFC-134a in a home refrigerator. *International Journal of Ambient Energy*, *43*(1), 2339-2350.

[41] Gao, E., Cui, Q., Jing, H., Zhang, Z., & Zhang, X. (2021). A review of application status and replacement progress of refrigerants in the Chinese cold chain industry. *International Journal of Refrigeration*, *128*, 104-117.

[42] Pigani, L., Boscolo, M., & Pagan, N. (2016). Marine refrigeration plants for passenger ships: Low-GWP refrigerants and strategies to reduce environmental impact. *International journal of refrigeration*, *64*, 80-92.

[43] De Paula, C. H., Martins, L. V. S., Duarte, W. M., & Maia, A. A. T. (2020). Thermo-Economic and Environmental Analysis of A Vapor Compression Refrigeration System Using R744 as a Replacement for R134a, ENC-2020-0135*, 18th Brazilian Congress of Thermal Sciences and Engineering (encit 2020),* November 16-20, 2020 (Online).

[44] Entec, U. K. (2002). Limited. Quantification of emissions from ships associated with ship movements between ports in the European Community, 87. A report for the European Commission, July 2002.

[45] World Bunker Prices, 2022. [Online] https://shipandbunker.com/prices. [Accessed 04 October 2022].