Conference Paper

Comparative Study on Coolbox/Waterloop and Natural Refrigerants Solutions for Commercial Refrigeration

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Abstract

This paper presents some natural and artificial solutions for reducing the use of HFCs in commercial refrigeration systems to limit greenhouse gas (GHG) emissions to the atmosphere. Additionally, the case study of a medium size supermarket is addressed. For this, a series of cooling systems have been sized which are divided into Coolbox/Waterloop systems and centralized systems. Three centralized systems with R410a, R717 and R744/R717 were dimensioned as well as a Coolbox/Waterloop system with R410a. This way is possible to ensure a comparison not only between fluids but also between the Coolbox/Waterloop technology and the centralized solution. After sizing the systems, the comparative energy, economic and carbon emission studies of the systems, in which their application has been found to be possible, are presented. After analysing the systems covered and the studies performed, it is concluded not only about the best applicable system, but also about the limitations found in each of the others.

Keywords: Natural refrigerants, Commercial refrigeration, Coolbox, Waterloop

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1. Introduction

Environmental protection has been a concern in the world population for some years now, given the increasingly relevant impact of climate change. The reduction and limitation of greenhouse gas (GHG) emissions, such as Hydrofluorocarbons (HFCs), is already implemented through very strict rules and regulations such as Kyoto Protocol (1997) and the F-gas Regulation (2014). With the need to drastically reduce GHG emissions, it is important to study less harmful solutions to the atmosphere. Emissions from refrigeration systems have a considerable direct emissions component resulting from the leakage of fluorinated gases used [1]. This component can be eliminated by using natural fluids, which have almost zero direct emissions. However, it is necessary to study these solutions to ensure that the systems are appropriate in terms of efficiency and cost.

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2. Coolbox/Waterloop System

The Coolbox/Waterloop system has the objective of reducing the total GHG emissions from refrigeration systems in commercial applications. It is common to use this type of systems with high Global Warming Potential (GWP) refrigerants. GWP is a measure system to acknowledge the GHG potential production of a refrigerant in comparison to CO_2 [1]. This system, which is suitable for small and medium-sized supermarkets, is based on the installation, next to the refrigerated cabinets and chambers, of Coolbox refrigeration units interconnected in a water condensing loop (Waterloop), shown in Figure 1.

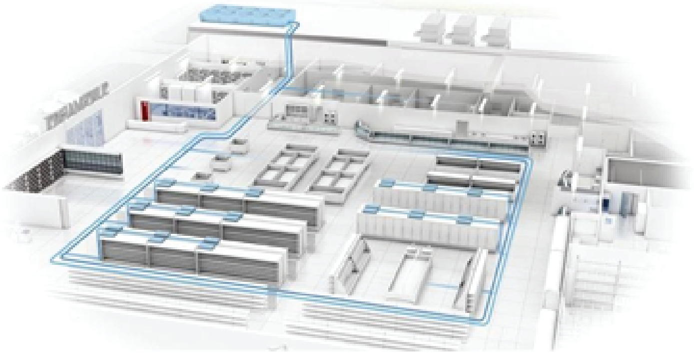

Figure 1: Example of a Coolbox/Waterloop solution implementation on a commercial surface Source: [2]

Coolbox units are compact equipment for installation at the base or top of cold rooms or cabinets. This equipments contain the various elements of a refrigeration cycle, except for the evaporator located inside the cold room or refrigerated display, with a single compression stage and condensation through a heat exchanger, fed by water as secondary fluid [3].

The use of this solution results in a substantial reduction (about 80%) of the refrigerant load in the installation, allowing high reductions on the direct contribution of the same to the Total Equivalent Warming Impact (TEWI) [3]. Additionally, there is an almost total reduction (about 96%) of refrigerant leakage resulting from factory assembly and testing. This type of installation reduces the need for field welding, which results in lower exposure of the general public to refrigerant and environmental pollution. This technology also allows easier changes in the arrangement of refrigeration equipment (and insertion of new ones) in the store. The size of the Coolbox units and the reduction in space reserved for the refrigeration equipment's results in a sales area increase. Finally, this solution makes it easy to maintain through localized and non-impact interventions on other cold production equipment. It also allows quick replacement of units using quick connectors [3].

3. Natural Refrigerants Solutions

Reducing the use of HFCs in refrigeration is only part of the environmental protection process. Energy used by refrigeration systems accounts for about 65% of total emissions, while the remaining 35% comes from direct emissions. In industrialized countries the commercial areas account for 3-4% of annual energy consumption and the refrigeration systems account for 35-50% of energy consumption. Therefore, it is necessary to keep in mind an energy efficiency mentality in their development [4].

Nowadays there are many solutions for cooling systems using natural refrigerants. Here are some of the most commonly used solutions for commercial refrigeration.

3.1. Hydrocarbons

The use of hydrocarbons in refrigeration is mainly limited to equipment with reduced refrigeration capacity due to their risk of explosion. In this way the circuits tend to be simple, hermetic, with as few connections as possible and with reduced use of electrical devices to avoid sparks. Additionally, the offer of compressors in the market, while vast, also allows only very small cooling capacities. However, the advantageous thermodynamic and transport properties of hydrocarbons, associated with the use of higher viscosity oils in order to ensure longer compressor lifespan, make hydrocarbon systems a viable solution for this type of equipment. The equipment's for commercial use, in which the hydrocarbon solution is mostly used, are self-powered such as refrigerated displays, vending machines, wine cellars, ice machines, counters and refrigerated cabinets, among others [5, 6].

Cooling systems with the addition of a chiller can also be energy viable. In this type of systems, the condensation is carried out through a chiller that operates, for example, with R290. The main advantage of this configuration is the adaptation of the condensing temperature by R290 and not the rest of the system, significantly reducing energy consumption. In this way it is possible to obtain good energy efficiencies even in hot climates with very low amounts of refrigerant load in the Chiller [7, 8].

Figure 2 shows the energy savings of natural fluid chiller systems, compared to the R744/R404a cascade system, at various locations with different climates.

The use of Chiller systems with R290 or R717 is found to provide energy advantages, over the R744/R404a, in every given location. It is also noteworthy that the R717 Chiller system allows for greater energy savings over the R290 Chiller system. Additionally, it is possible to verify that both systems guarantee greater energy gain in warmer places,

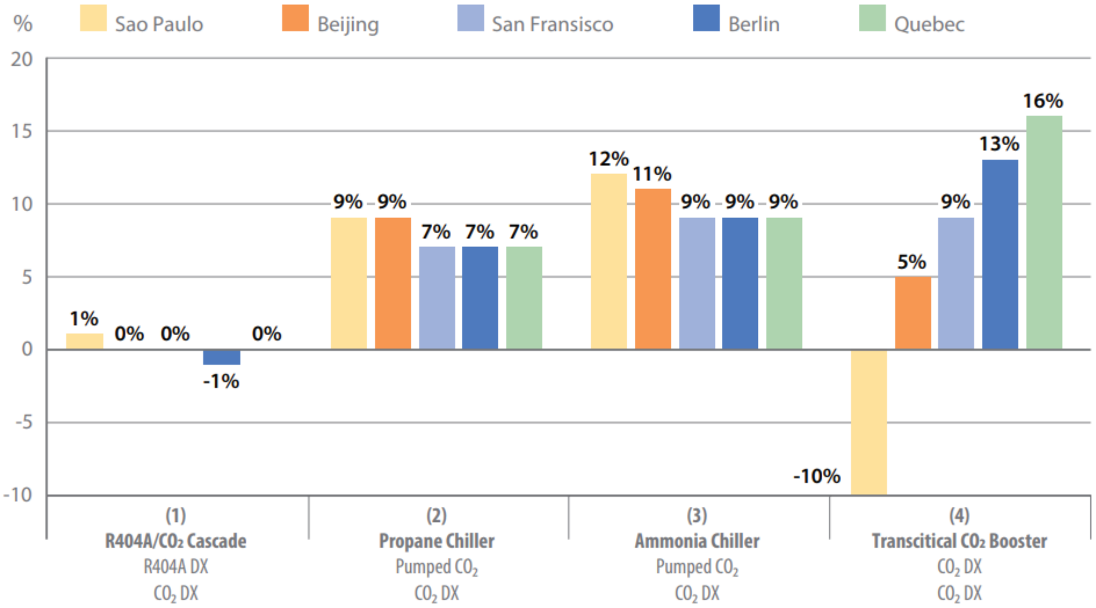

Figure 2: Energy efficiency comparison of several natural fluid solutions in different locations Source: [7]

given the increase in energy consumption of the R744/R404a system in this type of climate. For colder climates it is possible to see advantages in the consumption of the R744 Booster system [7]. This system advantages and disadvantages will be discussed in chapter 3.2.

3.2. Carbon Dioxide

A carbon dioxide system, where condensation occurs below the critical point, is called a subcritical system. However, since the critical point of the R744 is 31.1 °C and 73.6 bar, it is difficult to develop a system to operate in the hottest days of the year in many areas of the planet. For this reason, this type of solution is not usually implemented with the simplicity of other fluorinated gas systems. Since the operation of a subcritical R744 system causes problems with condensation temperatures above its critical point, a system with compressors capable of raising the R744 pressure to levels above the critical point is implemented. This type of system, which oscillates between a subcritical and overcritical state, is called a transcritical system. Thus, since the pressure of the R744 in subcritical systems is much higher than the operating pressure of other refrigerants in similar systems and considering that switching to overcritical means a significant increase in system pressure, all system components must be specially prepared to withstand the operating pressure of the R744. One of the differences in transcritical system equipment from the subcritical system is the replacement of the usual condenser with a gas cooler. This equipment provides the cooling of the refrigerant in the gaseous state without changing its phase. In standard transcritical systems, gas cooler pressure control is performed to achieve optimum capacity or maximum efficiency while always keeping the pressure below the maximum allowable [9]. The R744 transcritical systems are of some interest in small commercial refrigeration applications, heat pumps, portable air conditioning and supermarkets installed on large commercial surfaces [1]. The transcritical system can be adapted for the Low Temperature (LT) and Medium Temperature (MT) simultaneous use. This type of system, commonly called Booster system, is based on the unique use of R744 for both LT and MT circuits. To ensure system operation, the R744 is cyclically operating in transcritical or subcritical regimes. The use of two compression stages is necessary as the discharge temperature of the R744 is high causing oil deterioration [9]. This system is based on two compression stages so that the refrigerant from the LT evaporators is compressed initially in a subcritical regime and then, together with the refrigerant from the MT evaporators, is compressed again up to the condensing pressure already in transcritical regime. Figure 2 shows the lack of energy efficiency in hot climates of this type of system. However, particularly in colder climates, the gain in energy efficiency can be considerable [7]. The energy inefficiency of Booster systems, in hot climates, makes this solution of limited application. To counteract this inadequacy, parallel compression and multiple injection technologies have been introduced into these systems to achieve efficiencies, especially in hot climates. Parallel compression replaces flash gas recirculation upstream of the compressor. To reduce compression work, the flash gas is directed to an additional compressor where it is compressed with a lower pressure ratio. This way, the original compressor will compress only a part of the system's refrigerant and consume less energy. This technology allows higher efficiencies resulting from lower compression power and pressure ratios [10]. Compared to standard Booster systems, this type of solutions allows energy efficiency improvements, between 2 and 17% depending on the climate and architecture of the systems in which they are implemented. Reducing the required compressor capacity also results in reductions in the initial installation cost [11].

Figure 3 presents the results at study that analyse various cities of the world with different climates. As mentioned earlier and it can be seen in this study, the Booster system is not preferable to the R404a system, in hot climates. However, it has energy advantages in colder climates. By properly applying parallel compression or multiple injection systems in appropriate cases, considerable energy savings can be achieved over the R404a system, in all locations analysed. It is also found that the energy savings obtained by using multiple injection solutions are superior, in any climate, to the parallel compression solution [11, 12].

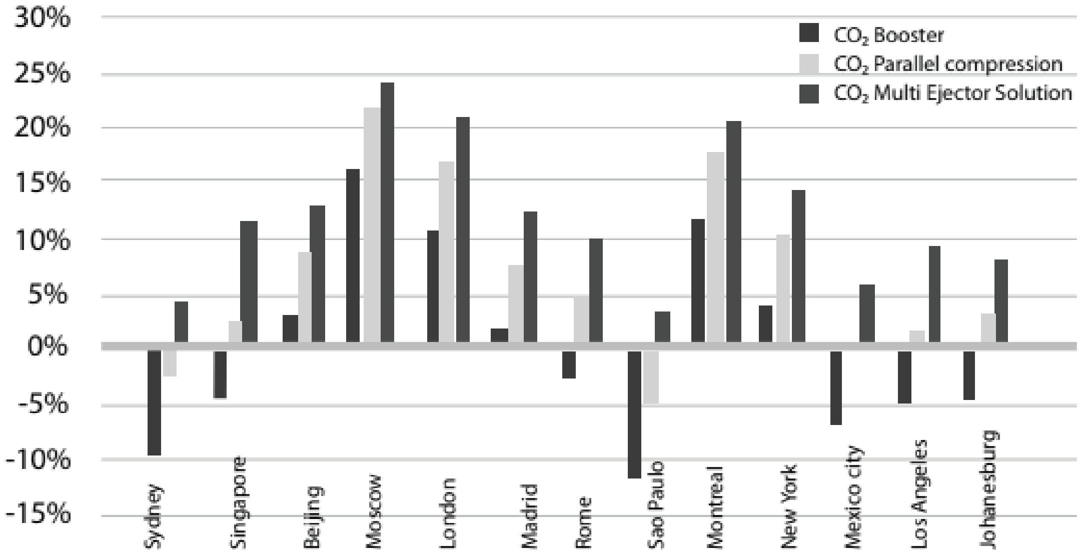

Figure 3: Energy consumption comparison between various systems at different locations compared to R404a Source: [11]

3.3. Ammonia

Ammonia-only refrigeration systems are not commonly used in commercial refrigeration. This is due to the high toxicity of this refrigerant, requiring the application of various equipment and safety measures. The main safety measure is the exclusion of the presence of this refrigerant in areas of coexistence with consumers and workers. Therefore, for the application of this solution in supermarkets, it is necessary to implement secondary circuits with an energy transport element, such as propylene glycol [1].

Just as with hydrocarbons, R717 can be used in Chillers. Although the use of chillers with R717 is more common in the industrial sector, due to the high refrigeration capacity in these machines, this solution also provides advantages in terms of system energy efficiency while keeping a low fluid load. As mentioned in chapter 3.1 and presented in Figure 2, R717 Chiller system allows for greater energy savings over the R290 Chiller system [1].

3.4. Cascade systems

Cascade systems comprise the use of two different refrigerants in different circuits [7]. In this way, it is possible to ensure advantageous efficiencies with fluids suitable for the temperature regimes assigned to them even in warmer climates [13]. These types of systems comprise the heat exchange between the two circuits through a heat exchanger that acts as a condenser/evaporator depending on the circuit in question. In this way, the heat absorbed in the LT circuit is rejected to the MT circuit through this same exchanger and, afterwards, is discarded outwards again through a condenser. In the cascade system, with R744 LT circuit and R717 MT circuit, each circuit has an appropriate fluid in terms of energy efficiency at their temperature range. This type of system is commonly used when it is not possible to reach the required evaporation and condensation temperatures only by applying a fluid in a vapor compression cycle. The two circuits are interconnected by a heat exchanger where the circuit with R744 rejects temperature to the circuit with R717. It, through a condenser, rejects heat to the outside with favourable energy efficiency [14]. Compared to a system using HFCs, the R744/R717 cascade system requires smaller equipment and fewer compression stages. In addition, the use of natural fluids avoids worrying about disposal legislation and their purchase price is lower [15].

4. Supermarket Case Study

This study is based on a supermarket located in Lisbon city centre. For the sizing of the systems it was considered that the conditions inside the supermarket are constant with values of 25 °C and 60% relative humidity. The outdoor temperatures of dry bulb and wet bulb given by Pack Calculation Pro software are 36.8 °C and 21.2 °C, respectively. As can be seen in Figure 4, the supermarket under consideration consists of the sales area, where the refrigerated displays are located, and the cold storage area. Additionally, next to the cold rooms area is the technical area, where the refrigeration system, pumping system, heating, ventilation and air conditioning (HVAC), domestic hot water and electrical switchboards are implemented. It is also considered that the supermarket is open to the public between 9am and 9pm every day.

The implemented cold rooms, shown in blue in Figure 4, are divided into four separate operating modes, frozen, refrigerated, climate controlled and neutral. For comparative analyses, neutral chambers were not considered as they are climate controlled using HVAC. Following a similar approach to that taken for the cold rooms, refrigerated displays, shown in green in Figure 4, also fall into frozen, chilled, neutral and hot displays. There are stand- alone exhibitors in the supermarket (cold and hot) that, as they are not connected to the refrigeration facility, were not considered. In total, the refrigeration and freezing requirement is 77.8 kW and 6.96 kW, respectively.

In order to verify the benefits of adopting the Coolbox/Waterloop solution as an alternative to centralized systems with HFCs, the Coolbox/Waterloop system and the centralized system were sized both with the R410a refrigerant. The Coolbox/Waterloop

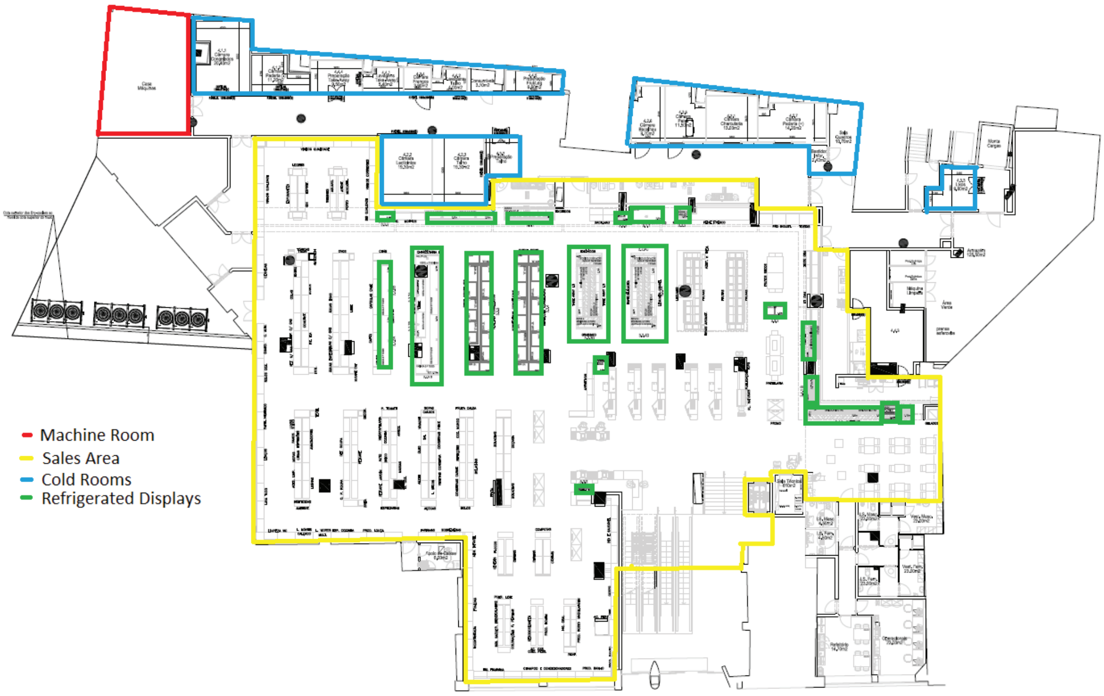

Figure 4: Studied supermarket layout

system is composed of cold production units dedicated to one or two exhibitors / cold rooms evaporators. These units are cooled by the 26/22 ºC outdoor heat-rejecting water piping system. This system has a two-pump rack located in the Machine Room. To ensure water cooling of the Coolbox/Waterloop system, the use of outdoor evaporative coolers/condensers was considered in all systems. For a more accurate analysis of the Coolbox/Waterloop system, it is intended to split the R410a centralised system into two circuits (LT and MT) in order to compare the energy efficiencies of the compressors. Each of these circuits feeds the respective evaporators of the exhibitors / cold rooms through compressors located in the Machine Room.

Then, in order to verify the advantages of using natural fluids in commercial refrigeration systems, these were economically sized and analysed. Since hydrocarbon compressors do not have large refrigeration capacities, with cooling capacities up to 2 kW only, they were not considered. Given that the ammonia installation is not safe in the sales area, the system operating with it was coupled with two secondary circuits with aqueous propylene glycol mixtures. In this way each of the secondary circuits absorbs heat from the assigned evaporators. In turn, the R717 absorbs the heat rejected by the circuits and rejects it outside the commercial area. This method allows a high level of safety to be maintained for all supermarket users. Since the carbon dioxide system could not operate under these condensing temperature conditions, either by the limitations of its subcritical regime or by limiting the compressors to the compression ratio level, a cascade system was designed with carbon dioxide in the LT circuit, aqueous mixture of propylene glycol in the MT circuit and ammonia in the condensation circuit. This type of system allows a high level of safety and good energy efficiency due to the efficient behaviour of R744 in LT circuits.

During the systems sizing, Danfoss Coolselector 2 software was used to calculate piping systems dimensions and compressor selection. Bitzer software was also used to get a comparison for the best compressor for each application.

For the emissions analysis, the TEWI calculation is based on refrigerant charge, GWP, annual leakage, recycling as well as system expected lifespan, annual energy consumption and equivalent CO_2 emissions on energy production. For the economic analysis only the initial systems costs, annual energy consumption and electricity costs in Portugal where considered. Maintenance costs were not included in this analysis as it was not possible to obtain their values.

5. Results and Discussion

In order to verify the advantages and disadvantages of using each system developed, energy, economic and emission analyses were performed based on the trial Pack Calculation Pro software from IPU. Parameters are defined and inserted in the software for the simulation such as system configuration, operating temperatures, exterior conditions, selected compressors and operating schedule. Given the information mentioned above, the software runs simulations where it can calculate the annual consumption of energy. Table 1 shows the obtained annual consumptions of each system.

Table 1: Comparison of annual electrical consumption of scaled systems System

System	Coolbox/Waterloop R410a	R410a	R717	R744/R717
Annual consumption [kWh]	131 705	114 653	136 361	131 117

As can be seen, the centralized system with R410a is the most economical in terms of electricity consumption while the centralized system with R717 proves to be the largest consumer. These consumptions result from a series of factors, one of them being the difference in energy efficiency of each system. As for the annual energy consumption simulation, the software also runs a simulation for the systems total Energy Efficiency Ratio (EER). These values are more accurate since they account for the systems behaviour all year round and not only the compressor manufacturer technical information. In Table 2 can check the total EER values from each cooling circuit and each system.

TABLE 2: EER comparison of each circuit of the dimensioned systems

System	Coolbox/Waterloop R410a	R410a	R717	R744/R717
EER LT	1.29	2.10	1.76	6.24
EER MT	3.99	4.08	3.65	3.66

The EER from the MT circuit of the centralized system with R410a is slightly higher than the other systems while the ERR from the LT circuit of the system incorporating both R717 and R744 is much higher than the others. As expected, the R744's high EER verifies its better performance when condensing in a heat exchanger with lower temperatures. However, the much higher R744 EER in the frozen circuit is not enough to make this system more efficient than the R410a centralized system. This inability results from the large difference in refrigeration demand between the frozen and refrigerated circuits. The requirement of the frozen circuits of the dimensioned systems corresponds to 6.97 kW while that of the refrigerated circuits corresponds to 77.8 kW. Since the frozen circuit accounts for just over 8% of the total system refrigeration requirement, the EER of this circuit's compressors makes a very small contribution to the overall energy performance of the system. Besides that, the use of water circulation pumps in addition to those used in evaporative condensers, that are common to all circuits, or aqueous mixtures of propylene glycol results in additional energy consumption by systems having them. Since the centralized system with R410a is the only one that does not have these circulating pumps, it is natural that there is a decrease in consumption compared to the other systems.

Although all alternative systems to the centralized system with R410a have higher electrical consumptions, they have somewhat similar consumptions and are all consuming between 14 to 19% more electricity. However, since energy consumptions only correspond to indirect greenhouse gas emissions, it is necessary to analyse the emissions of the various sized systems considering the refrigerants used in them. Figure 5 shows the comparison of the emissions of the scaled systems.

As would be expected it can be seen from Figure 5 that not only does the R410a centralized system have a much higher TEWI than the other sized systems (about 140% more) but this difference is largely due to the direct emissions of the same as the systems all have very close consumptions and thus similar indirect emissions. The existence of this high direct emission value in the centralized system with R410a is as much due to the large amount of high GWP (GWP = 2088) refrigerant in circulation as to the typical leakage rate of a centralized system.

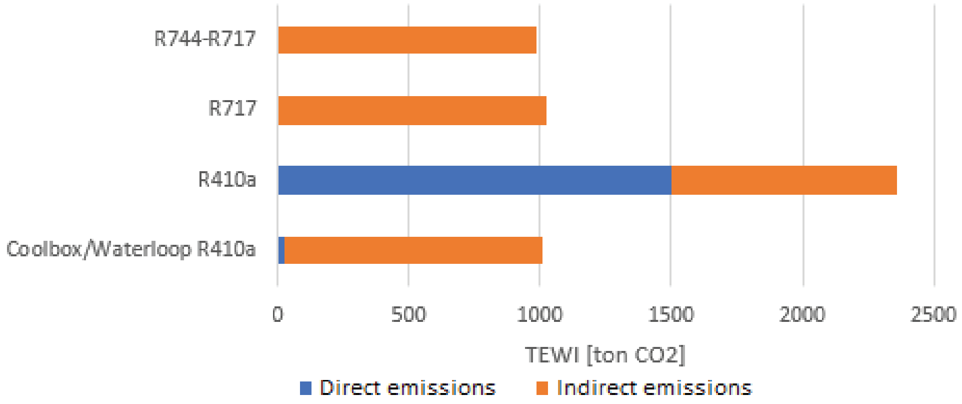

Figure 5: TEWI of each scaled system

Centralized systems with natural fluids only have indirect contribution since the circulating fluids in the system have practically no GWP. Due to the substantial reduction in leakage rate and circulating fluid mass compared to the R410a centralized system, the R410a Coolbox/Waterloop system has residual direct emissions resulting in a TEWI similar to the natural fluids sized systems.

Given the need to obtain the implementation costs of each system, a Portuguese refrigeration and air conditioning company provided these same approximate costs in order to obtain a more accurate analysis. These costs were based in similar and approximated systems to the ones referred. However, in order to maintain confidentiality, the implementation costs of the systems are shown in a percentage record. Table 3 shows the implementation costs of each system compared to the centralized solution with R410a.

Table 3: Percentage difference in approximate installation cost of each system

System	R410a	Coolbox/Waterloop R410a	R717	R744/R717
Installation cost [%]	-	-16.7%	-9.3%	+9.3%

To economically compare the sized systems, it was taken in consideration the installations initial cost, energy consumption and Portugal energy cost. Since sufficient information could not be obtained, maintenance costs were not considered in the calculations. Additionally, no inflation, system amortization or any other aspect besides the mentioned above were taken in consideration. For calculation purposes, twenty years system lifespan was arbitrated. Figure 6 shows the difference in installation costs after twenty years of operation. For the same reasons, as well as the presentation of installation costs, the operating costs of the systems are presented in percentage differences.

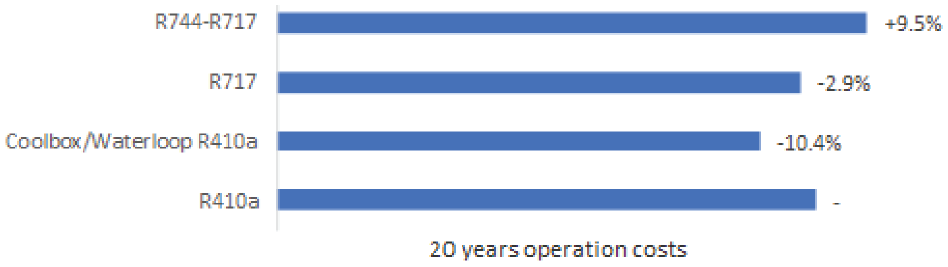

Figure 6: Total cost comparison of systems implemented after 20 years

Since electrical consumptions do not differ substantially between systems, the difference in their implementation and operation costs results in a comparison like that developed in comparing implementation costs only.

Given the analyses performed it is possible to confirm that the use of R410a, or other high GWP HFCs, in centralized systems generates GHG emissions much higher than those with natural fluids and systems with HFCs adapted to have low refrigerant loads (Coolbox/Waterloop system). This is due to the high direct contribution to TEWI, product of the high GWP from R410a. It also shows that the use of some of these solutions, although less energy efficient, results in a smaller financial investment for this case study.

6. Conclusion

To reverse the increased use of HFCs in refrigeration systems, natural refrigerants come up with appropriate solutions for each type of system. Nowadays technology allows them to be no longer limited by their difficult implementation.

This study analyses centralized systems with R410a, R717 and R744, as well as a Coolbox/Waterloop system with R410a, to verify not only the advantages of using natural fluids but also to study the consequent improvement by reducing the amount of HFC used in the system. It can be concluded that the Coolbox/Waterloop system with R410a is the most economically viable (10.4% savings) even though it has no lower consumption than the centralized system with R410a. Although the centralized system with R717 has the highest electrical consumption, it has also proved to be a more economical system (2.9% savings) than the centralized system with R410a after twenty years given its lower implementation cost.

With respect to the R744/R717 centralized system, although it is an energy efficient system optimized for both circuits and with less consumption of systems that produce less direct emissions to the atmosphere, the cost of implementing such a system is considerable and only would have economic advantages when implemented in larger systems. Given the similarity of the total emission values of the Coolbox/Waterloop R410a, centralized R717 and R744/R717 systems, and presenting the best operating cost within 20 years, it is assumed that the Coolbox/Waterloop system with R410a presents the best alternative of the analysed systems for the implementation of a low TEWI system in this supermarket. For selecting a system operated with natural refrigerants with similar emissions and lower operating costs within 20 years compared to the centralized system with R410a is the system with R717.

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