FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Assessment of TEWI (Total Equivalent Warming Impact) of different supermarkets with different technologies

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Mestrado em Engenharia Mecânica

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Porto, 2025

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Abstract

This dissertation, carried out within the scope of the curricular unit Dissertation of the Master's Degree in Mechanical Engineering during the second semester of 2024/2025 at the Faculty of Engineering of the University of Porto, is the result of the project developed at RACE S.A.

The main objective of the study is to determine the Total Equivalent Warming Impact from three supermarkets with different types of refrigeration systems, by evaluating their direct and indirect CO_2 equivalent emissions. While indirect emissions are linked to the energy consumed to run the refrigeration systems, direct emissions are caused by refrigerant leaks. The refrigeration systems analyzed are a decentralized solution using plug-in and remote condensing units, a CO_2 transcritical system and a cascade system using CO_2 and an HFC.

The analysis starts by getting to know each supermarket, the quantity of refrigerant charge needed, leakage rates, system operating lifetime, all of which contribute to the total CO_2 equivalent emissions. Energy consumption data for the supermarkets were gathered using monitoring systems, and TEWI calculations were performed for each system, providing a comprehensive comparison of their environmental impacts. In addition, the total volume of cold rooms and the Total Display Area (TDA) of the display cabinets were calculated to establish some TEWI metrics to better understand the behavior of each system.

Apart from the environmental evaluation, an economic study of the systems was conducted to calculate the estimated Capital Expenditures (CapEx) and Operational Expenditures (OpEx) for every refrigeration solution. This makes it easier to determine which supermarket refrigeration systems are the most cost-effective.

Finally, TEWI and long-term investment results were compared for each solution. The most efficient solution from an environmental perspective is the centralized transcritical CO_2 system, which has the lowest TEWI/Vol and TEWI/TDA. On the other hand, despite being less energy efficient, the decentralized system is the cheapest in terms of initial investment. The cascade system has been shown to be the most environmentally harmful since it uses a high GWP refrigerant and has significant leakage rates, even though it is still in use in some installations. Therefore, it is determined that the transcritical system with CO_2 represents a more sustainable option for the future of commercial refrigeration, even though these systems require a higher initial investment.

Keywords: *Total Equivalent Warming Impact (TEWI), Commercial Refrigeration, Supermarkets, Refrigeration Systems, Direct and Indirect Emissions, Transcritical CO_2 Systems, Cascade Systems, Plug-in Units, Remote Condensing Units*

Resumo

A presente dissertação, realizada no âmbito da unidade curricular Dissertação de Mestrado em Engenharia Mecânica durante o segundo semestre de 2024/2025 na Faculdade de Engenharia da Universidade do Porto, é o resultado do projeto desenvolvido na RACE S.A.

O principal objetivo do estudo é determinar o Impacto Total de Aquecimento Equivalente (TEWI) de três supermercados com diferentes tipos de sistemas de refrigeração, avaliando as suas emissões diretas e indiretas de CO_2 equivalente. Enquanto as emissões indiretas estão ligadas à energia consumida para operar os sistemas de refrigeração, as emissões diretas são causadas por fugas de refrigerante. Os sistemas de refrigeração analisados são uma solução descentralizada utilizando unidades condensadoras remotas e *plug-in*, um sistema transcrítico de CO_2 e um sistema em cascata utilizando CO_2 e um HFC.

A análise começa por conhecer cada supermercado, a quantidade de carga de refrigerante necessária, as taxas de fuga, a vida útil do sistema, tudo isto contribuindo para o total de emissões equivalentes de CO_2. Os dados de consumo de energia dos supermercados foram recolhidos através de sistemas de monitorização, e foram realizados cálculos TEWI para cada sistema, fornecendo uma comparação abrangente dos seus impactos ambientais. Além disso, foi calculado o volume total das câmaras frigoríficas e a Área Total de Exposição (TDA) dos expositores frigoríficos para estabelecer algumas métricas de TEWI para uma melhor compreensão do comportamento de cada sistema.

Para além da avaliação ambiental, foi realizado um estudo económico dos sistemas para calcular as despesas de investimento (CapEx) e as despesas de manutenção (OpEx) estimadas para cada solução de refrigeração. Isto torna mais fácil determinar quais os sistemas de refrigeração de supermercados mais económicos.

No final, os resultados de TEWI e de investimento a longo prazo foram comparados para cada solução. A solução mais eficiente do ponto de vista ambiental é o sistema CO_2 transcrítico centralizado, que apresenta o menor TEWI/Vol e TEWI/TDA. Por outro lado, apesar de ser menos eficiente em termos energéticos, o sistema descentralizado é o mais barato em termos de investimento inicial. O sistema em cascata demonstrou ser o mais prejudicial para o ambiente, uma vez que utiliza um refrigerante com um GWP elevado e apresenta taxas de fuga significativas, embora ainda seja utilizado em algumas instalações. Assim sendo, determina-se que o sistema transcrítico com CO_2 representa uma opção mais sustentável para o futuro da refrigeração comercial, mesmo que seja necessário um maior investimento inicial.

Palavras-Chave: Impacto Total do Aquecimento Equivalente (TEWI), Refrigeração Comercial, Supermercados, Sistemas de Refrigeração, Emissões Diretas e Indiretas, Sistemas Transcríticos de CO_2, Sistemas em Cascata, Unidades Plug-in, Unidades Condensadoras Remotas

UN Sustainable Development Goals

The United Nations Sustainable Development Goals (SDGs) provide a global framework to achieve a better and more sustainable future for all. It includes 17 goals to address the world's most pressing challenges, including poverty, inequality, climate change, environmental degradation, peace, and justice.

The specific Sustainable Development Goals that can be suitable in this study have the following names:

SDG 9 Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation energy for all

SDG 12 Ensure sustainable consumption and production patterns

SDG 13 Take urgent action to combat climate change and its impacts

SGD	Target	Contribution	Performance Indicators and Metrics
9	9.4	Adoption of cleaner and more sustainable technologies, promoting the conversion of existing infrastructures to more efficient options aligned with the principles of the circular economy and carbon neutrality.	Increase in the energy efficiency of the evaluated systems.
12	12.4	Assess the environmental impact associated with supermarket refrigeration systems, which often use refrigerant gases with high global warming potential (GWP), such as hydrofluorocarbons (HFCs), guiding the choice of cleaner and more efficient technologies.	Decrease of leakage rates.
13	13.2	Identify which refrigeration technologies and configurations in supermarkets have the lowest climate impact. The work can point out ways to adopt more efficient and environmentally friendly technologies, promoting their integration into public policies on energy efficiency and emissions reduction.	Accountability of Total Equivalent Warming Impact (TEWI) and its consequently gradual reduction.

Acknowledgements

I would like to express my deep gratitude to all the people who, in some way, contributed to the completion of this work.

I would like to thank, first of all, my supervisor at FEUP, Professor Eliseu Monteiro, for his technical guidance, availability, prompt response and patience throughout this process. Your help, suggestions and support were essential for the development of this dissertation.

To the entire RACE S.A. team, I would like to thank you for answering all my questions, for your collaboration and provision of data, as well as for the opportunities to learn and apply concepts in the real context of commercial refrigeration systems. I would like to thank Engineer Clara Coelho, supervisor at the company, and also Engineers João and Sebastião for sharing their practical knowledge about refrigeration systems in supermarkets, which greatly enriched my research.

To my friends who were by my side throughout these 5 years full of experiences, laughter, moments of sharing, beautiful memories and moments in which we supported each other.

To my boyfriend Gonçalo, for always being there when I most needed.

To my parents, for always believing in me and for supporting me daily in my decisions and throughout this beautiful journey that has so many ups and downs.

This work is the result of the support I had from all these people, to whom I am eternally grateful.

Inside each of us there is still the kid who had a dream.

Contents

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List of Acronyms

α	Recovery Factor
β	Indirect Emission Factor
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CapEx	Capital Expenditures
CFC	Chlorofluorocarbon
CSR	Cold Storage Rooms
DEC	Direct Electrical Energy Consumption
E_{annual}	Annual Energy Consumption
EEF	Electricity Emission Factor
GHG	Greenhouse Gases
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HVAC	Heating, Ventilation and Air Conditioning
HVAC&R	Air Conditioning and Refrigeration
IEA	International Energy Agency
INE	*Instituto Nacional de Estatística*
IPCC	Intergovernmental Panel on Climate Change
IPMA	*Instituto Português do Mar e da Atmosfera*
IPPI	Industrial Producer Price Index
L_{annual}	Annual Leakage Rate
LT	Low Temperature
m	Refrigerant Charge
MT	Medium Temperature
n	System Operating Lifetime
ODP	Ozone Depletion Potential
OpEx	Operational Expenditure
PI	Promotional Islands
SC	Supermarket with Cascade system
SR	Supermarket with Remote condensing units
ST	Supermarket with Transcritical system
RCU	Remote Condensing Unit
RDC	Refrigerated Display Cabinet
REC	Refrigeration Electrical Energy Consumption
TDA	Total Display Area
TEC	Total Energy Consumption
TEWI	Total Equivalent Warming Impact

Chapter 1

Introduction

This dissertation was carried out within the scope of the Master's Dissertation in Mechanical Engineering curricular unit during the second semester of 2024/2025 at the Faculty of Engineering of the University of Porto (FEUP). This first chapter describes the motivation and main objectives of the project. Along with this, the company's history, the methodology followed throughout the project and the structure of the report are also covered.

1.1 Framework and Motivation

The types of refrigeration systems used in commercial refrigeration, as well as the characteristics of refrigerants, have a substantial impact on both direct and indirect greenhouse gas emissions. As a result, supermarkets represent a sector with significant potential for developing strategies and mechanisms to help reduce these emissions, whether through technological updates or more informed decision-making, as well as the integration and study of indicators such as TEWI.

In line with the European Union's environmental targets, particularly the NetZero plan and the phase-down of HFCs under the F-Gas Regulation, the refrigeration industry is geared towards adopting more sustainable solutions. The present dissertation was created in partnership with RACE S.A., a Portuguese company that specializes in designing solutions for refrigeration and HVAC systems. Based on the company's activity and strategic direction, the need arose to conduct a comparative analysis of various refrigeration system configurations used in real commercial contexts. This study aims to help make better-informed technical and economic judgments about future solutions with a smaller environmental footprint.

The motivation of this work, from a technical perspective, is to understand how different systems (stand-alone, remote condensing or central systems) perform in terms of energy use and refrigerant charge requirement and, from an environmental perspective, to quantify and compare the total impact of CO_2 equivalent emissions of each configuration, using real operational data and the TEWI methodology, thus providing a decision support tool.

1.2 Objectives

The main goal of this research is the assessment of Total Equivalent Warming Impact (TEWI) of different supermarkets that use different technologies/solutions. To achieve this it will be needed to firstly, identify different refrigeration solutions, decentralized and centralized, that still operate nowadays. Study one solution with only built-in equipment (remote condensing units and plug-in units), study one solution with a CO_2 transcritical system and another centralized solution with CO_2 and another refrigerant, preferably a HFC, since CO_2 is a refrigerant that is gaining exponential growth as a refrigeration solution for supermarkets but there is still plenty of refrigeration infrastructures operating with synthetic refrigerants.

For each study, analyze in detail the floor plan of the supermarkets, categorize its display cabinets and evaporators, in order to find the data necessary to calculate TEWI. This data is the type of refrigerants used, refrigerant charge, annual leakage rates, system operating lifetime, indirect emission factor, recovery factor and annual energy consumption, that can be obtained from catalogs and data collected by the control system of supermarkets.

After this, the calculation of the direct and indirect emissions for each case follows, establishing some TEWI metrics and comparisons with the results obtained.

Finally, perform an economic analysis to understand the total cost of each solution and make a more informed decision when choosing a refrigeration infrastructure.

1.3 Company Background

RACE S.A. is a company with value-added engineering solutions for the customer, contributing to well-being, safety and comfort, with innovative and sustainable technologies.

More than three decades after entering the market with refrigeration and air conditioning services for commercial and industrial spaces, RACE is now focusing on its most valuable strategic areas to strengthen its presence in international markets with innovative, competitive and sustainable solutions, many of which were developed from scratch by its engineering team.

With a legacy of over 5,000 installations carried out nationally and internationally, RACE is also a brand focused on the future and structured on knowledge, engineering, technologies and Research&Development geared towards the main challenges of the sector.

The company has new technical solutions for the fields of Refrigeration, HVAC and Building Efficiency, and has the conditions to consolidate themselves as the engineering partner of reference for their customers.

Figure 1.1: Logotype of RACE S. A.

1.4 Methodology

The methodology followed in this work can be described in the following steps:

1. Literature review about energy consumption in commercial refrigeration, CO_2 and GHG emissions, system solutions for supermarkets, refrigerated display cabinets, concept of TEWI, refrigerants and refrigeration cycles;

2. Selection of the supermarkets studied, each representing a distinct refrigeration solution: decentralized system (plug-in units and RCUs), centralized transcritical CO_2 system, cascade system with CO_2 and R134a;

3. Collection and characterization of technical data through various supplier catalogs and technical datasheets for refrigerated display cabinets (model, TDA, theoretical energy consumption, refrigerant charge), cold storage rooms (volume, evaporator power, defrost type), remote condensing units (RCUs), compressors and ice machines;

4. Collection and analysis of real consumption data, obtained from the monitoring systems installed in the supermarkets;

5. Determination of more parameters for TEWI calculation, such as annual leakage rate, refrigerant recovery factor and equipment lifetime (based on After-Sales Department records) and projection of electricity emission factor for 2024;

6. TEWI calculation for each supermarket, with direct and indirect emissions;

7. Definition of comparison metrics between systems for TEWI such as TEWI/TDA and TEWI/Vol (TEWI per TDA of display cabinets and TEWI per room volume of cold storage rooms);

8. Estimation of investment and maintenance costs (CapEx/OpEx).

1.5 Dissertation Structure

This dissertation is organized into five main chapters: Introduction, Bibliographic Review, Characterization of Supermarkets, TEWI Calculation and Conclusions.

- Chapter 1 presents the motivation behind the study, the objectives to be achieved, and the context of the company where the work was developed. It also includes an overview of the dissertation structure.
- Chapter 2 provides the theoretical background necessary to understand the concepts explored in the work. It reviews the energy consumption of supermarkets, types of refrigeration systems and display cabinets, the concept of TEWI, environmental legislation, refrigerants currently in use and prohibited, and refrigeration cycles.
- In Chapter 3 the characterization of the selected supermarkets is done, describing three solutions in detail: Supermarket A, Supermarket B and Supermarket C. For each store is characterized its refrigeration system, existing display cabinets, refrigerant charge, TDA and estimated energy consumption. This chapter also presents and discusses the actual energy consumption data of each supermarket.
- In Chapter 4, all the collected data to determine the TEWI for each supermarket is gathered. This chapter also presents the considerations made about equipment lifetime, leakage rates, and electricity emission factor. After this, some comparisons between the values of TEWI metrics are made. The chapter finishes with an economic estimate of CapEx and OpEx.
- The last chapter brings together the themes developed throughout the study. Furthermore, some questions about future work were addressed.

Chapter 2

Bibliographic Review

2.1 Introduction

The increasing awareness for environmental sustainability has motivated the search for more efficient and less harmful alternatives in several sectors, such as commercial refrigeration, since this sector may have ample investment options in energy efficiency and emissions reduction. Supermarkets contribute significantly to greenhouse gas emissions since they are large energy users and have refrigeration equipment that run constantly on electricity produced from fossil fuels. In this context, the evaluation of TEWI (Total Equivalent Warming Impact) becomes an essential tool for measuring and quantifying the environmental impact of greenhouse gas emissions from the different refrigeration system configurations that can be used in these establishments [1].

All of the theoretical concepts mentioned are important to fully understand refrigeration in supermarkets, energy balances, GHG emissions and GWP, F-Gas regulation and types of refrigerants on the actual market.

This chapter presents the theoretical basis necessary for understanding TEWI, addressing its concepts, calculation methods and determining factors as well as its future comparative analysis for different supermarkets, allowing the identification of the variables that most influence this indicator and possible strategies for reducing greenhouse gas emissions. In addition, the main refrigeration systems used in supermarkets, the corresponding refrigeration cycles and the different types of equipment are also reviewed. A summary of the past, present and future of the refrigerants area is also provided, always taking into account its environmental impact to mitigate the effects of emissions associated with commercial refrigeration.

2.2 Energy outlook of supermarkets

As part of the European Green Deal, the EU countries have committed to significantly reduce greenhouse gas (GHG) emissions, with the best scenario being the Net Zero, that corresponds to achieve a total of zero emissions of CO_2 until 2050. Energy consumption in buildings, residential and commercial/public services, accounted for about 28% of the global final energy consumption in 2022 (Figure 2.1). In European countries, this value corresponds to 32% (almost one-third of total energy consumption). More in depth, on a global scale, only the commercial/public services was responsible for consuming 8% of the total final energy, but if only electricity consumption is considered, commercial sector accounts 20% of the total final consumption (data collected from the IEA World Energy Balances 2024 Highlights for the year of 2022) [2]. The form of energy used in refrigeration display cabinets is electricity and, in general terms, supermarkets can consume 3–5% of the total electricity in industrialized countries [3].

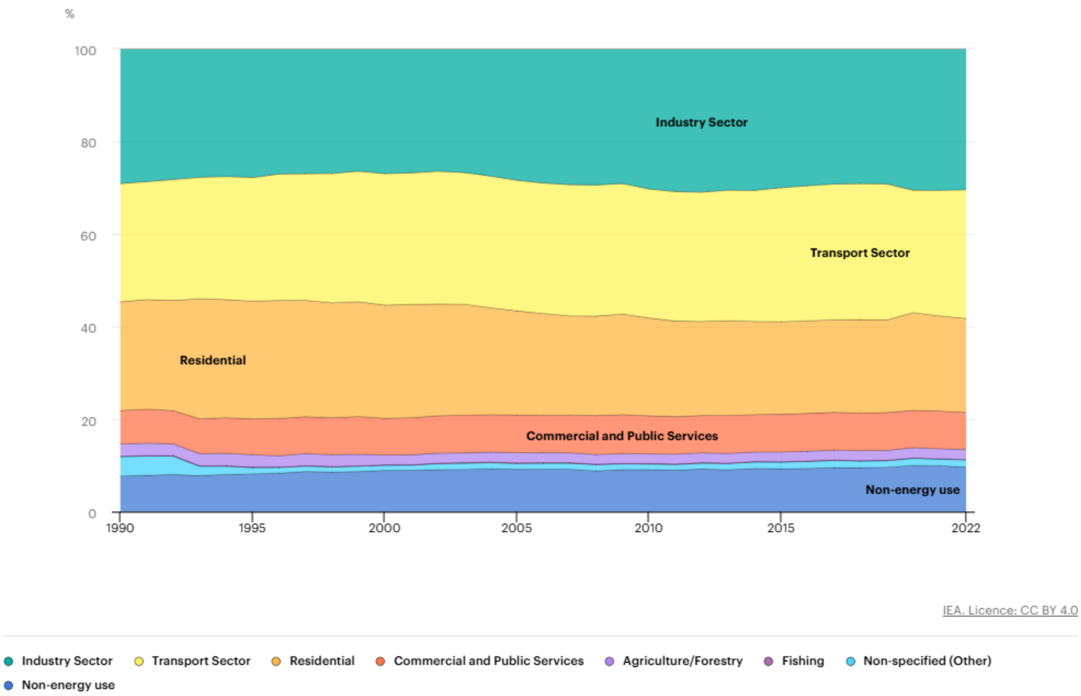


Figure 2.1: Total final energy consumption by sector, World 1990-2022 [4].

The main energy needs of a supermarket are refrigeration, heating, ventilation and air conditioning (HVAC) and lighting, but sometimes there are more needs in relation to its potential exploitation, which could include cooking if there is a bakery or cafeteria, or perhaps offices with computers [3]. Figure 2.2 illustrates an estimate about the percentage of energy consumed for the different demands of a supermarket, according to [5], although it can have certain oscillations depending on the supermarket. With so many perishable products such as meat, fresh fish, eggs or frozen goods at very low temperatures being sold in stores, refrigeration is expected to have a large share of a supermarket's energy expenditure.

In terms of CO_2 emissions, globally, in Figure 2.3 it is possible to see that the quantity of Mt CO_2 is increasing year after year and the *Buildings* sector detains 8 942 Mt CO_2 from a total of 34 116 Mt CO_2 emitted in 2022, corresponding to about 26% of total emissions. "Others" refers to emissions from fishing, forestry, agriculture, other energy industry own use and other final consumption that isn't otherwise mentioned.

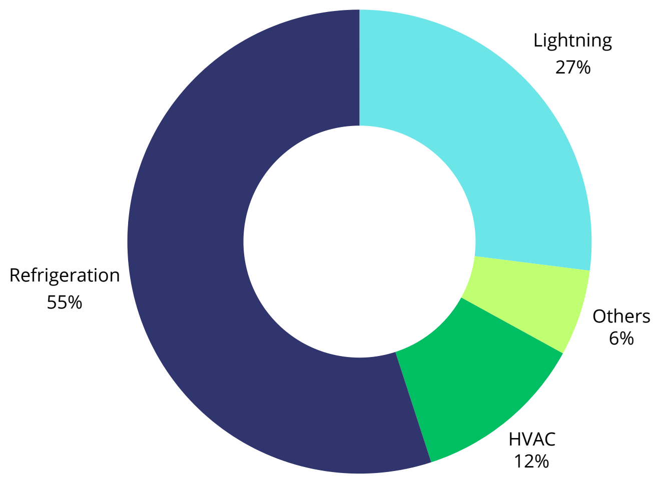


Figure 2.2: Typical Allocation of Energy Consumption in a Supermarket [5].

These calculations for the *Buildings*' sector emissions take into account direct fuel combustion (from natural gas, for example) and indirect emissions from electricity and district heat consumption (reallocated from the power and heat generation sector).

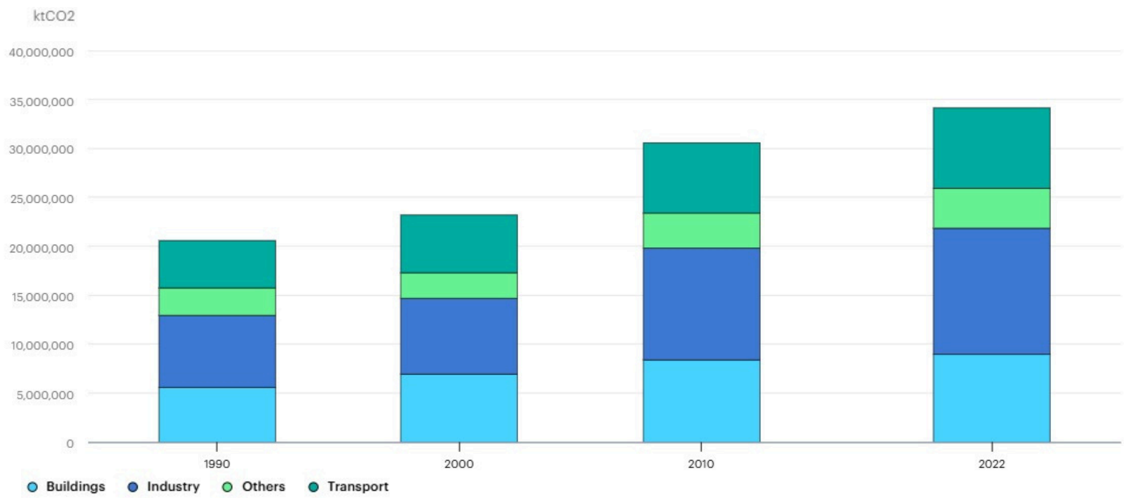


Figure 2.3: Total CO_2 emissions from fuel combustion by sector with electricity and heat reallocated, World 1990-2022 (adapted) [6].

In Portugal, the account for consumption of final energy for supermarkets is inserted in the *Services* sector, according to the reports and data available. In 2022, this sector was responsible for 14.5% of the final energy consumed, in comparison to the global 8%, representing a consumption of 2393 ktoe (27% higher in relation to 2012) [7]. Figure 2.4 shows the representation of the consumption mix for *Services*, where it is possible to conclude that most of the energy used comes from electricity.

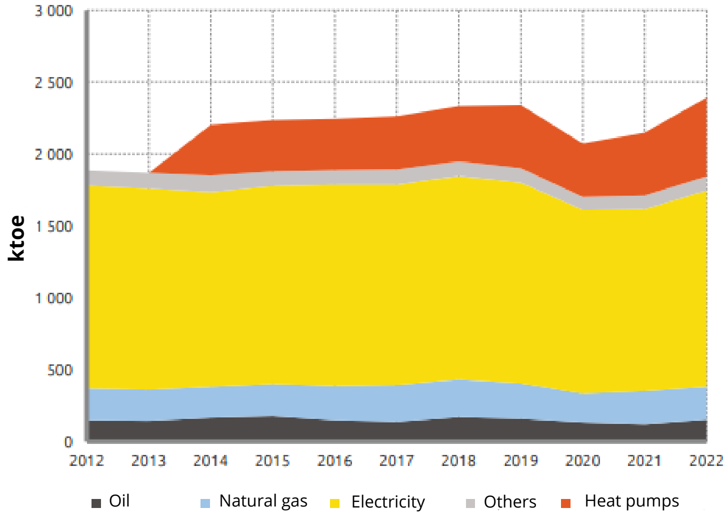


Figure 2.4: Consumption on the *Services* sector (adapted from [7]).

If the objective is to get to know how much CO_2 is emitted by electricity, one can resort to the Electricity Emission Factor, which is an indicator of the quantity of CO_2 emitted by unit of electricity consumed. The annual EEF of recent years in the context of the Portuguese energy mix can be consulted in Table 2.1 and in the report "*Fator de Emissão da Eletricidade - 2024*" [8].

Table 2.1: Annual Electricity Emission Factor (based on [8]).

Region	Unity	2018	2019	2020	2021	2022
Continent	tCO_2e/MWh	0.283	0.225	0.175	0.153	0.157
Madeira	tCO_2e/MWh	0.493	0.524	0.505	0.465	0.480
Azores	tCO_2e/MWh	0.448	0.450	0.435	0.462	0.465
Portugal	tCO_2e/MWh	0.288	0.234	0.184	0.164	0.169

2.3 Identification of refrigeration solutions for supermarkets

GHG emissions are intrinsically linked to the type of refrigeration system chosen for a given supermarket, since using suitable equipment is very important for its energy efficiency. Supermarket refrigeration systems can be separated into three categories:

- **Stand-alone systems**: Small sealed systems that combine all the refrigeration components, evaporator, condenser, compressor and expansion valve into a factory-built unit. This plug-in display cases can be, for example, ice cream freezers or beverage vending machines. These solutions are widely found in small shops and very busy infrastructures like train stations, colleges or hospitals. They are particularly common because they are affordable, easy to place or transport anywhere and their setup is simple (just plug it into the socket), which make them a good investment. As a disadvantage, they are less efficient than other solutions due to their high energy consumption per unit. They operate in a similar way to household refrigerators and these units utilize a minimal refrigerant charge (typically between 0.1 and 0.5 kg). R290 (propane) is becoming the most used refrigerant for this type of systems and is expected to dominate this market [9] [10].

Figure 2.5: Example of a Stand-Alone System (beverage cooler) [10].

- **Remote condensing units**: These are medium sized systems that consist in a factory built condensing unit that contains a compressor and a condenser, as the name suggests; it is located outside of the sales area and is connected by a network of pipes through which the refrigerant passes by in direction to one or more refrigerated display cases (where the evaporator is), as it is schematically illustrated in Figure 2.6. This type of equipment is used in small shops like bakeries, convenience stores or restaurants. Its usual capacity is 1 to 10 kg of refrigerant [9] [10].

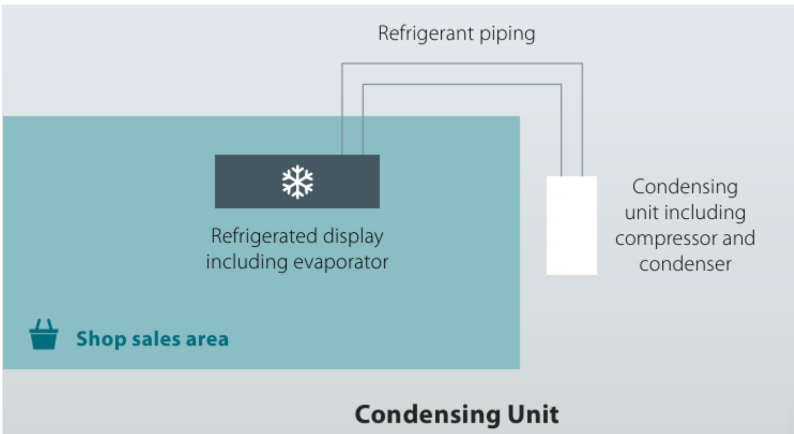


Figure 2.6: Schematic example of a Condensing Unit [9].

- **Central systems**: Large supermarkets are usually cooled using central systems. Central systems consist in multiple display cases that are connected, by refrigerant piping, to a multi-compressor rack that stays outside the sales area and with condensers that are located outside the supermarket, like it is represented in Figure 2.7; the number of compressors can vary depending on the installation. This configuration is the one that requires the biggest initial investment and can stand great amounts of refrigerant, between 20 to 300 kg. For example, a store can have one central system for chilled products and a second and independent central system for frozen products. Large supermarkets can also have some stand-alone systems or remote condensing units, for example, for freezer islands. It is more common for a central system to have more leaks due to the large piping networks and also because it has a larger refrigerant charge [9] [10].

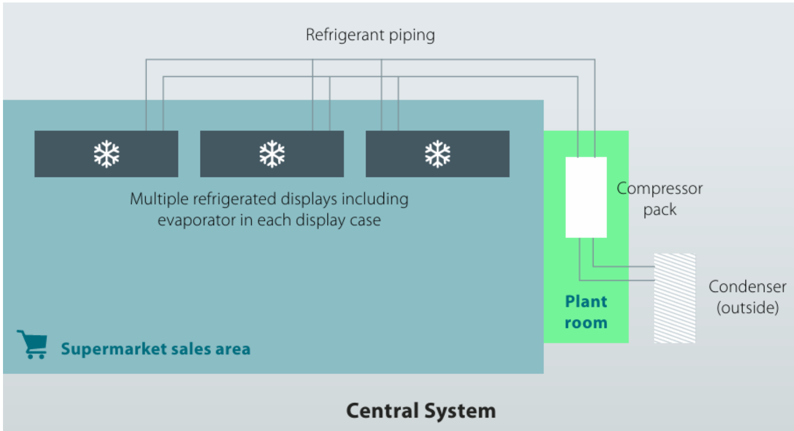


Figure 2.7: Schematic example of a Central System [9].

For better understanding, Figure 2.8 represents a refrigeration plant used in this type of configuration, where it is possible to see the compressors.

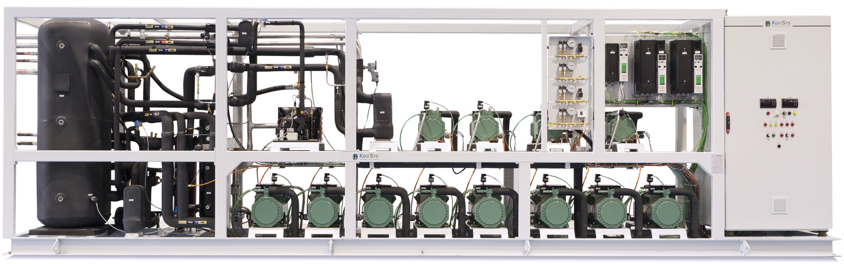


Figure 2.8: Example of a refrigeration plant (Courtesy of RACE S.A.).

All these types of equipment can be used for both chilled and frozen products. The big difference is that for stand-alone systems there is no require nor specialized refrigeration skills for installation, they are fully charged with refrigerant at the factory and usually all they need to begin to operate is an electrical source. In contrast, condensing units and central systems necessitate a piping network to connect the various components, so it is mandatory to have an on-site installation and qualified hand-work. Some important characteristics of this three equipment types are shown in Table 2.2. It is also important to address the problem of noise coming from compressors. Most often, remote condensing units are located on the rooftop of buildings due to compressor noise and heat release from the gas cooler. Central systems have the compressor rack outside the storage area and the condenser/gas cooler also stays on the rooftop. Stand-alone systems are placed on the sales area and have a built-in compressor, so this feature is a problem always tried to be minimized.

Table 2.2: Characteristics of refrigeration equipment (based on [9]).

Parameter/Equipment	Stand-alone	Condensing unit	Central system
Cooling capacity [kW]	0.1 - 1	2 - 20	30 - 200
Annual leakage rate [%]	<1	5 - 20	10 - 30
Refrigerant charge [kg]	0.1 - 0.5	1 - 10	20 - 300
Peak emissions period	At end-of-life	Operating leakage	

As it can be seen from the table above, the choice for a supermarket refrigeration equipment is of primordial importance due to considerations on the current GHG emissions (leakage) and for safety decisions. For example, for working fluids such as R290 (propane), its high flammability makes that the refrigerant is subject to certain legislation that limits its maximum flow rate for use, so, applications in stand-alone systems can be considered as they have a very small refrigerant charge and extremely low leakage levels. However, if considering a central system, where the refrigerant charge is significantly larger, this would not be a suitable choice due to safety concerns. Also, central systems are the most energy-efficient in terms of electricity consumption, so their CO_2 emissions are primarily due to having the highest refrigerant leakage rate [9] [11]. Many of this systems are nowadays being installed using R744, especially in Europe, as it will be presented further ahead.

It is important to notice that these configurations can coexist within the same supermarket and the choices made can be based on different interests that are intended to be achieved, for example, minimum costs, greater energy efficiency, good use of existing space or lower TEWI, which is the objective of this study and will be explored next.

2.4 Identification of refrigerated display cabinets

Commercial refrigeration equipment is designed to store and display chilled and frozen products for customer access in food retail and service locations, such as supermarkets or convenience stores. In a supermarket, refrigeration is needed for cabinets on the sales area to store perishable foods but also for cold storage rooms outside the sales area to conserve the products until they are ready to be displayed [3].

Energy consumption can be reduced by optimizing stores' internal conditions, temperature and humidity, and also with the implementation of the advances in refrigeration technologies that improve system layout and components. Nowadays systems also operate more efficiently, with lower refrigerant charges and reduced leakage. Recent improvements in display cases include efficient lighting, fans and the existence of doors [3].

Cabinets and cold storage rooms can be classified according to their storage temperature. If the cabinet is utilized to store chilled products it is a Medium Temperature cabinet (MT), or also "positive", with an evaporation temperature of -7/-10ºC and the temperature in the cabinet should be above -1/0ºC (and below 7ºC depending on the product stored). For Lower Temperature cabinets (LT), also denominated as "negatives", the temperature at the evaporator must be -32/-35ºC and the frozen products require a temperature at the cabinet below -18ºC [10].

Refrigerated Display Cabinets (RDC) can be connected to a central system, being called Remote Display Cabinets, or can have an incorporated condensing unit, denominated by Plug-in Unit. Remote display cabinets only have the evaporator inside them, with the other components like compressors or condenser being connected trough a piping network. Plug-in units have all the necessary components to replicate a refrigeration cycle inside them [12].

According to Eurovent (European Industry Association for Heating, Ventilation, Cooling, and Refrigeration), cabinets can be separated into 5 categories [12]:

- Semi-vertical and vertical with doors
- Multideckers and semi-vertical open
- Service counters
- Combi freezers
- Islands

To ensure a notable reduction in electricity consumption, some island display cabinets are equipped with low-power demisting and defrosting systems. Also, the existence of doors instead of open cabinets reduces energy losses to the supermarket's environment; actually, this can reduce the cooling load required for a display cabinet by around 50%, according to [9] . Figures 2.9 to 2.13 illustrate some examples of cabinets by category, adapted from a supplier's catalog [13].

Figure 2.9: Vertical with doors.

Figure 2.10: Multidecker.

Figure 2.11: Service counter.

Figure 2.12: Combi freezer.

Figure 2.13: Island.

2.4.1 Climate Class

The climate class for refrigerated display cabinets refers to the dry bulb temperature and relative humidity in which the equipment was projected to operate efficiently and according to performance specifications. According to EN ISO 23953 2:2015, standard for commercial equipments, there are nine climate classes that correspond to different climate conditions around the world. For the region of Portugal, due to its temperate climate characteristics, Class 3 is assumed (ambient temperature equal to 25 ºC and relative humidity of about 60%, as it can be seen in Table 2.3).

Table 2.3: Some examples of climate classes.

Class	2	3	4	5	6	7
Dry bulb temperature [ºC]	22	25	30	40	27	35
Relative humidity [%]	65	60	55	40	70	75

If an equipment is used in a region whose climate conditions do not correspond to its class, the refrigeration cycle will not function properly, it will probably consume more energy and will not keep food at the appropriate storage temperature.

2.4.2 Energy Consumption Evaluation of Remote Refrigerated Display Cabinets

Total Electrical Consumption (TEC) is the sum of the energy consumption of the refrigeration compressor(s) with the secondary components, essential to correct operation of the system, such as evaporator fans, defrost heaters or lightning [12].

2.4.2.1 The Direct Electrical Energy Consumption (DEC)

This is the parameter that takes into account the power that has to be supplied to evaporators, lightning and defrost heaters as well as the period of time during which each of them needs to be supplied [12].

Direct Electrical Energy Consumption (DEC) characterizes the energy consumption of the electrical components of the cabinet/cold room, in kWh/24h. If talking about plug-in display cabinets, the DEC equals the Total Electrical Consumption (TEC), because all components are already incorporated in the equipment. For Remote Refrigerated Display Cabinets, compressors are outside the sales area but the evaporator, defrost heaters and lightning are inside the display cabinet, so the Total Electrical Consumption is the sum of DEC and REC [12].

2.4.2.2 Refrigeration Electrical Energy Consumption (REC)

REC is an important parameter to calculate the daily electrical energy consumption that is needed for the compressors to refrigerate remote units. When the desired temperature and humidity are reached, there is no need for compressors to work 24h or to work all at the same time, but this subjects will be addressed more in depth further in this study when talking about practical cases.

2.4.3 Total Display Area

The Total Display Area (TDA) refers to the entire visible area of food products and other goods of a display cabinet, including sections seen through glass. It is determined by adding the horizontally and vertically projected surface areas of the visible foodstuff, measured in square meters (m²) [12].

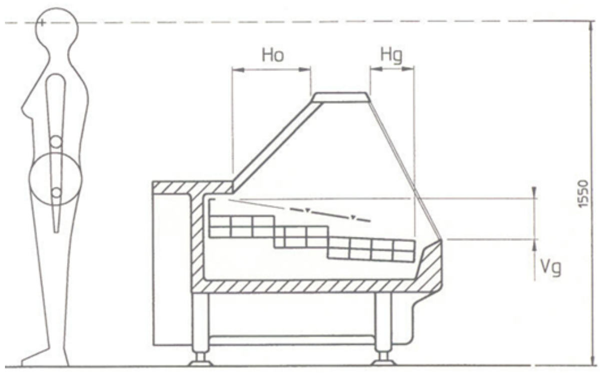
TDA can be calculated from Equation 2.1:

$$TDA = (H_o \times L_{oh}) + (H_g \times T_{gh} \times L_{gh}) + (V_o \times L_{ov}) + (V_g \times T_{gv} \times L_{gv}) \ [m^2] \tag{2.1}$$

Where:

H_o = Horizontal projection, open surface
V_o = Vertical projection, open surface
H_g = Horizontal projection, glazing surface
V_g = Vertical projection, glazing surface
T_{gh} = Light transmission through the glazing surface for horizontal projection
T_{gv} = Light transmission through the glazing surface for vertical projection
L_{oh} = Horizontal open surface length
L_{ov} = Vertical open surface length
L_{gh} = Horizontal glazing surface length
L_{gv} = Vertical glazing surface length

Figure 2.14 shows an example of how to calculate TDA for a service counter, according to Eurovent Guidelines [14].



	Loh = 2,40	Ho	0,350
Tgh = 90%	Lgh = 2,50	Hg	0,194
	Lov = 2,50	Vo	0
Tgv = 90%	Lgv = 2,50	Vg	0,185
TDA=(Ho*Loh)+(Hg*Tgh*Lgh)+(Vo*Lov)+(Vg*Tgv*Lgv)			1,693

Figure 2.14: TDA calculation example for a 2.5m length service counter cabinet [14].

2.5 TEWI

Supermarket refrigeration systems contribute significantly to direct and indirect global warming, as these systems operate approximately 24 hours a day, 365 days a year.

In December 1997, more than 160 nations gathered in the Japanese city of Kyoto to formulate enforceable greenhouse gas limitations for industrialized countries under the 1992 Framework Convention on Climate Change, resulting in the Kyoto Protocol, which established emission targets relative to 1990 levels [15].

The HVAC&R industry is an important subject in climate discussions because refrigerants such as CFCs, HCFCs, and HFCs emit significant amounts of greenhouse gases. In addition to that, the main impact of global warming from stationary refrigeration and air conditioning comes from electricity generation to power the equipment. TEWI showed up as being a measure of the global warming impact of an equipment based on the total released emissions of greenhouse gases (GHG), during its useful lifetime, for the case of refrigeration and air conditioning applications [15] [16].

TEWI takes into account the emissions from leakage of the working refrigerant (direct emissions) and the emissions produced through the consumption of energy while the equipment is operating (indirect emissions) [16]. Figure 2.15 explains how TEWI is the sum of this two types of emissions.

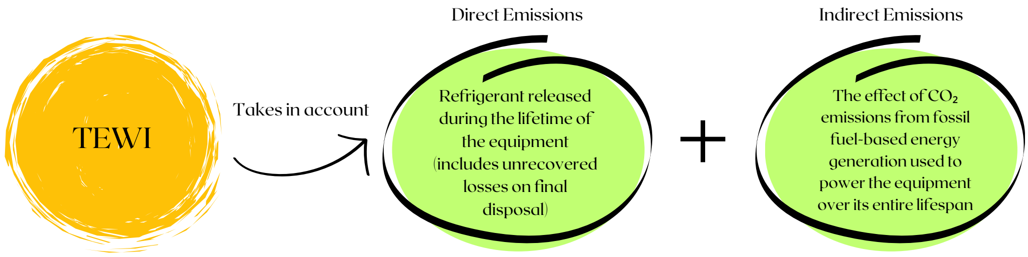


Figure 2.15: Definition of TEWI.

TEWI is often expressed in kilograms of carbon dioxide equivalent (kg CO_2e) and can be expressed has seen in Equation 2.2, took from [15]. The first two terms of the equation take respect to direct emissions and the last term is related to indirect emissions. This TEWI calculation method is applied to refrigeration and air conditioning systems that utilize vapor compression principles and rely on grid-connected electricity [16].

$$\text{TEWI}[\text{kg } CO_2e] = GWP \cdot L_{annual} \cdot n + GWP \cdot m \cdot (1-\alpha) + E_{annual} \cdot \beta \cdot n \tag{2.2}$$

Nomenclature:

GWP - Global Warming Potential of the refrigerant [kg CO_2e /kg]
L_{annual} - Annual leakage rate [kg/year]
n - System operating lifetime [year]
m - Refrigerant charge [kg]
α - Recovery factor (from 0 to 1)
E_{annual} - Annual energy consumption [kWh/year]
β - Indirect emission factor [kg CO_2e /kWh]

For example, having an α of 80% means that 80% of the refrigerant charge can be recovered by the end of the equipment's useful life.

2.5.1 Direct Emissions

There are four main types of leakages from HVAC&R equipment that can happen [16]:

- Gradual leaks during normal operation;
- Losses during maintenance;
- Catastrophic losses during normal operation (less likely to occur);
- Losses at the end of equipment's life.

A study reveals that the mainly causes of leakage are due to vibrations, improper operation, welding failure, corrosion and mechanical wear, being this one responsible for 64% of total causes. Mechanical wear can be divided into: loose connections, equipment damage, worn joints, worn gaskets, missing gaskets and covers, in order from greatest to least incidence [17].

Although projected with adequate caution, some literature estimates that, in supermarket cabinets, leakage rates are around 8-10% [15], but in fact, the actual leakage rate for a determined cabinet depends on the type of refrigerant, operating pressure and installation chosen. For example, it is expected that for a refrigerant that operates with lower system pressures its leakage rate will be lower than a system with a working refrigerant that operates with higher pressures. Due to high system working pressures, refrigerant leakage is very possible to happen during maintenance and repair [1].

Furthermore, for supermarket applications it is common to assume an expected equipment life of 10/15 years due to more severe operating conditions and possible transportation of some equipments from one infrastructure to another [15].

2.5.2 Indirect Emissions

Indirect emissions refer to the release of GHG resulting from the electricity consumption of supermarket refrigeration systems; this emissions depend on the energetic mix for electricity generation and the energy efficiency of the equipment. The corresponding electrical power data of the used equipments can be obtained from the manufacturers' datasheets [1].

In Figure 2.16, it is possible to analyze CO_2 emissions by type of refrigeration solution. As already mentioned, central systems are expected to have more direct emissions because their leakage rates are the highest ones but they are the most energy-efficient ones, in contrary to stand-alone systems.

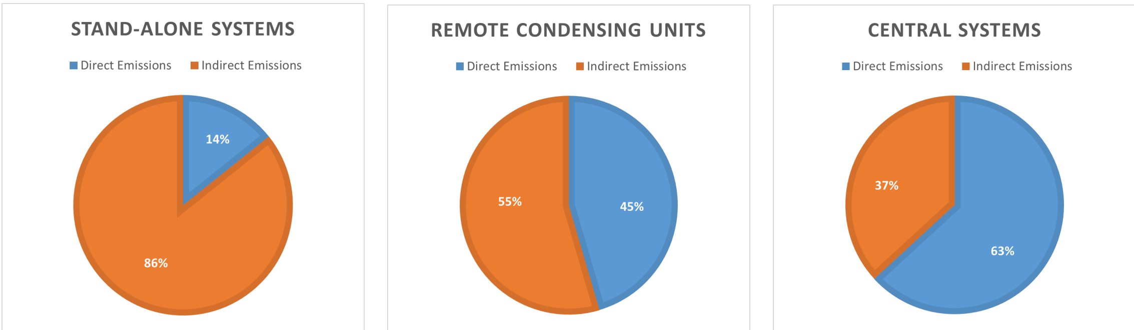


Figure 2.16: Direct and indirect emissions of CO_2 from Commercial Refrigeration in the EU, 2022 (percentages for millions of tonnes of CO_2, data from [9]).

2.5.3 Global Warming Potential

Global Warming Potential (GWP) is an indicator of environmental pollutants, introduced to assess the impact of different greenhouse gases on the climate in relation to the equivalent amount of carbon dioxide in the atmosphere; CO_2 takes the reference value of GWP=1. It represents how much heat a greenhouse gas traps in the atmosphere relative to CO_2, for example, if a gas has GWP = 1300, this means that 1 kg of that gas contributes as much to global warming as 1300 kg of CO_2 over a period of 100 years. The GWP index for CO_2 equivalence was first introduced in 1990 and was immediately incorporated into climate policy using a 100-year time horizon, referred to as GWP 100 [18].

In Figure 2.17, it can be seen the current GWP limitations for the using of refrigerants with high GWP, according to the F-Gas regulation.

The introduction of GWP was innovative as it considers both global mean Radiative Forcing (RF) and the atmospheric lifetime of a substance. Radiative Forcing is a disturbance in the Earth's climate radiation balance. Over time, GWP has become the standard and legislated metric for converting emissions of various gases into an equivalent amount of CO_2 emissions, being regulated by the IPCC [18].

Figure 2.17: F-Gas schedule & GWP limitations by equipment type [19].

2.5.4 Indirect emission factor (β)

Electricity can be produced from a range of fuels including gas, oil and coal, which can release high amounts of CO_2, but also from "clean" alternatives such as hydroelectric plants, wind power or photovoltaic panels. Each country has its own mix of primary sources for electricity generation, and this mix can change significantly from country to country depending on the economy and resources available. For the case of Portugal, this factor can be consulted in Table 2.1.

2.6 Refrigerants

By 1930, as it can be seen from Figure 2.18, chlorofluorocarbons (CFCs) were the most widely used refrigerants due to being non-toxic and non-flammable, which was safer to use in supermarkets, but when scientists discovered that this refrigerants were extremely harmful for the Ozone Layer, they were phased out following the introduction of the Montreal Protocol in 1987. Emissions of substances like R12 or R22, divided into chlorofluorocarbons and halons (HCFCs), with a high Ozone Depletion Potential (ODP), were controlled and forced to decrease as years went by, in order to protect the Ozone Layer. Then, the HFC generation of refrigerants started to appear, for which the ODP index took the value of zero. The Ozone Depletion Potential quantifies the extent of harm a substance can inflict on the ozone layer in relation to an equivalent amount of trichlorofluoromethane (CFC-11), which is assigned an Ozone Depletion Potential equal to 1.0. This has encouraged the use of gases such as R134a (CH_2FCF_3), one of the most widely used refrigerants in the world currently, used in automotive, commercial and residential air conditioning systems, replacing R12 [18] [20].

After the control of refrigerants with high ODP, concerns started to turn into GHG because HFCs contribute significantly to global warming. The most important protocol for the control of substances with high GHG emissions was the Kyoto Protocol, already mentioned before. With this Protocol, the next generation of refrigerants emerged, as it is presented in Figure 2.18. The Kyoto Protocol uses the Global Warming Potential (GWP) value to allow the determination of the

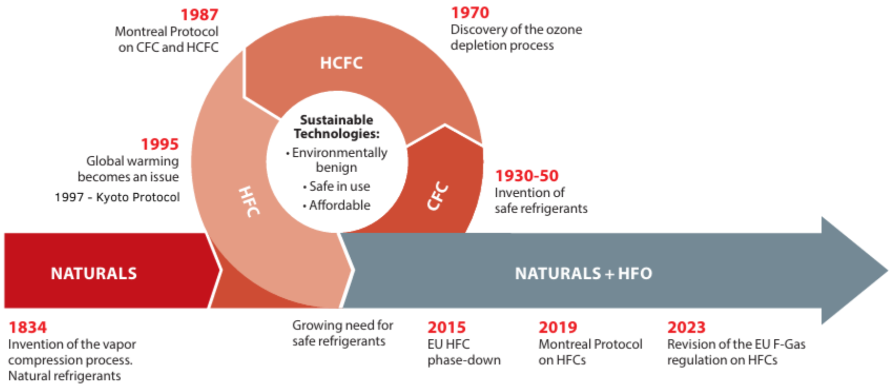


Figure 2.18: The refrigerant usage cycle (adapted from [19]).

impact of various GHG on the climate in relation to the equivalent of CO_2 accumulated in the atmosphere [18].

Still nowadays, the most common type of refrigerants used across the world are hydrofluorocarbons (HFCs), like R134a that has a GWP of 1430, which has a high global warming potential. To solve this problem, European Union applies the F-Gas regulations since 2006 to control their use and sale in the market, which is leading to the demand for another type of refrigerants with low GWP; the solution is now to focus on natural refrigerants, for example, R717 (also known as ammonia or NH_3), R744 and R290. HFOs are also being considered as a synthetic alternative; they were designed for being the substitutes of HFCs with low GWP [11].

Currently, the supermarket industry is focusing on using very-low GWP refrigerants to minimize global warming, as it is expressed in Figure 2.18, but many years ago, natural refrigerants where also the ones used; its use declined due to working complexity or safety precautions that could not be solved at that time.

2.6.1 R290

The refrigerant R290 is also known as propane and has the chemical formula $CH_3CH_2CH_3$.

R290 is a hydrocarbon very much used in heat pumps and commercial equipment. This fluid has an ODP = 0 and GWP = 3, which makes it compatible with the restrictions of the F-Gas regulation. It has thermodynamic properties similar to R22, and, although with lower capacity and working pressure, its thermal efficiency is high, especially at high temperatures, due to its low discharge temperature. Therefore, propane is an efficient and economical alternative to HFC gases in refrigeration, providing greater energy efficiency. On the other hand, propane has no odor, so it is difficult to detect the presence of leaks. Figure 2.19 presents some characteristics of this refrigerant [11].

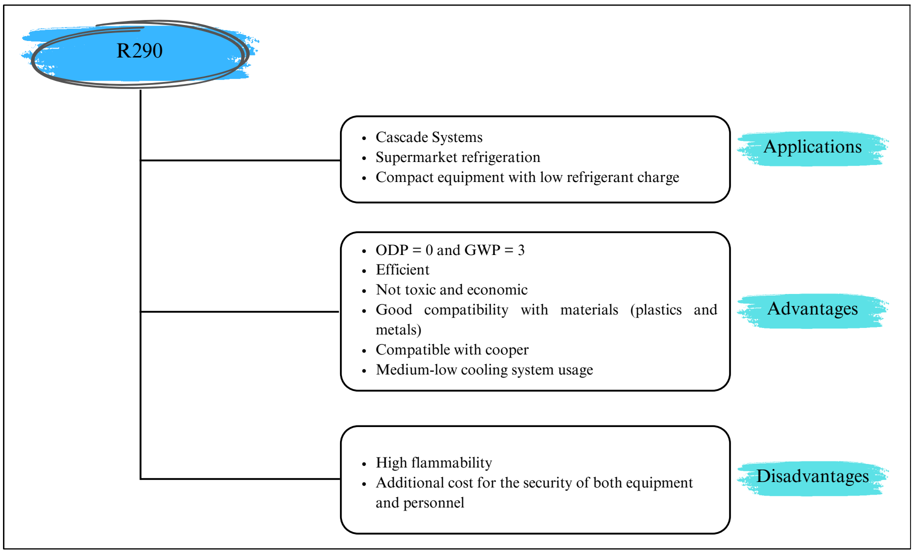


Figure 2.19: Characteristics of R290.

R290 has been used in hermetic commercial refrigeration equipment with a load limit of 150 g/circuit for interior spaces in Europe, due to its high flammability; ASHRAE classifies it as a Safety Class A3 refrigerant, the highest of classifications. However, the possible revision of the safety standards (IEC 60335-2-89 and IEC 60335-2-40) may increase this limit to 500 g/circuit, allowing for a potential increase in its usage. In Figure 2.20, all the conditions according to standard EN378:2016 for the utilization of A3 refrigerants are explained [21].

<table>
<tr><th>EN 378 : 2016
Charge limitations for flammable refrigerant A3</th><th>Compr & vessel indoors</th><th>Refrig equipment indoors
Compr & vessel outdoors</th><th>Machinery room or open air</th><th>Ventilated enclosure</th></tr>
<tr><td>General access
e.g. schools, hotel, hospitals, theaters</td><td colspan="2">Only sealed systems.
20% x LFL x room volume
Below ground : not more than 1 kg
Above ground : not more than 1,5 kg</td><td>5 kg</td><td rowspan="4">Max
130m³ x LFL

Max
5 kg R290
5 kg R1270
10,3 kg R610A
10,9 kg R430A</td></tr>
<tr><td>Supervised access
e.g. profesional offices, general manufacturing sites</td><td colspan="2">20% x LFL x room volume
Below ground : not more than 1 kg
Above ground : not more than 2,5 kg</td><td>10 kg</td></tr>
<tr><td rowspan="2">Authorised access
e.g. production of chemicals, food, … Refineries, non-public areas in supermarkets</td><td colspan="2">20% x LFL x room volume
Below ground: not more than 1 kg</td><td rowspan="2">No limit</td></tr>
<tr><td>Above ground not more than 10 kg</td><td>Above ground not more than 25 kg</td></tr>
</table>

Figure 2.20: Charge limitations for flammable refrigerant A3 according to EN378:2016 [21].

2.6.2 R744

The refrigerant R744 corresponds to carbon dioxide, CO_2, and it has been seen has a great alternative to substitute HFCs because of its ODP = 0 and GWP = 1. Besides being a GHG, it is abundant in the atmosphere and is a residual product of industry activities, so its easy to obtain. Because of this, CO_2 is also low-cost and usually there is no recovery and disposal when the useful lifetime comes to an end. In addition, it has a very high volumetric refrigerating capacity (latent heat trough phase changes): depending on the operating conditions, it can be between five to eight times as high as R22 or NH_3. This feature results in systems with high efficiency and low pressure drops, which leads to a need of very low flow rates, results in a reduction for the pipe diameter needed and lower energy requires for the operation pumps. It has no odor and it is more dense than air, so special measures have to be taken to prevent leakages and health issues [11] [22].

R744 has a low critic temperature of 31.06ºC and high pressures, has can be seen by its p-h diagram in Figure 2.21. Because of this special characteristics, R744 can work in the subcritical and transcritical regimes (below and above critical pressure, respectively) and can't be a replacement fluid for refrigeration systems that already exist. The system should be designed according to the features of this fluid, being important to notice that, in the case of transcritical systems, it is necessary to adopt more complex systems (parallel compressor, mechanical subcooling, etc.) to achieve efficiencies similar to the ones when operating with conventional fluids; this can result in higher equipment costs [11].

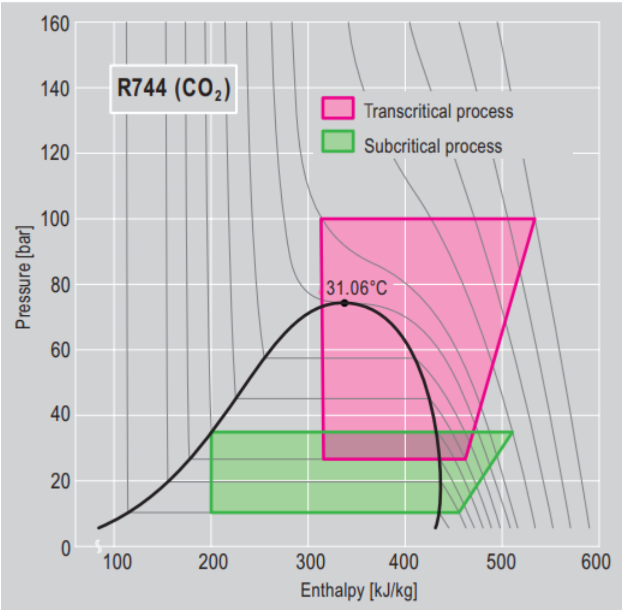


Figure 2.21: P-h diagram for Subcritical and Transcritical Regimes of R744 [22].

As it is in Figure 2.22, this versatile gas has the advantage of having a high heat transfer coefficient which has great results for heat transfer in evaporators and condensers. This fact allows for a selection of equipment with smaller dimensions, on the contrary to the equipments who use HFCs [11].

Figure 2.23 shows a remarkable growth of stores using transcritical CO_2 in Europe. From a total of 90 700 stores, 84% correspond to stores with a centralized system and 16% tell respect to stores with condensing units; there are also 4 900 industrial sites working on transcritical CO_2. As mentioned before, in Europe, new central systems are now being projected with R744 as the working refrigerant and currently the market penetration of commercial refrigeration using transcritical CO_2 represents 30% of the total number of stores [23].

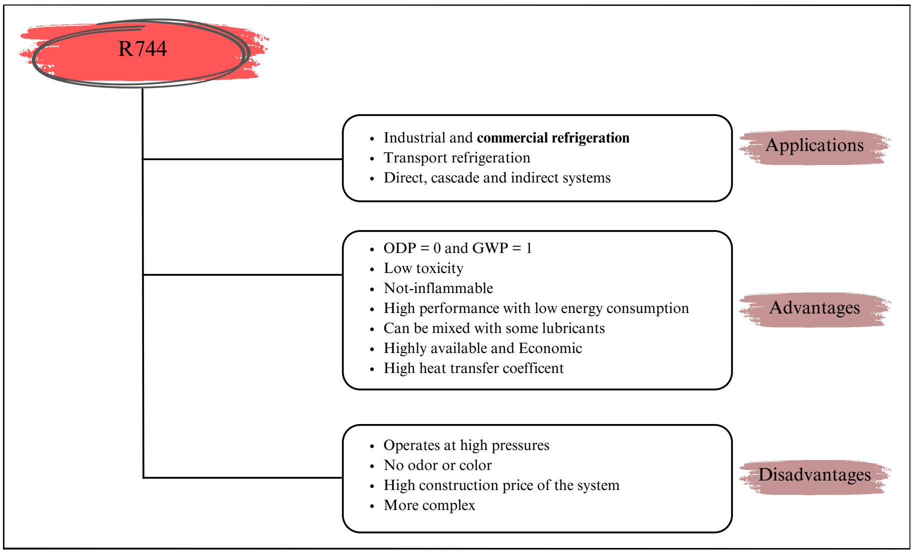


Figure 2.22: Characteristics of R744.

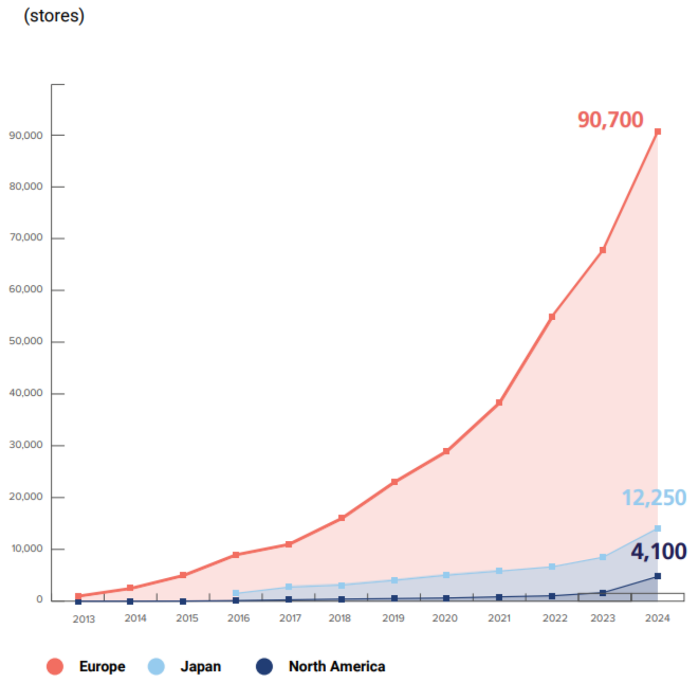


Figure 2.23: Transcritical CO_2 Installation Growth in Major Regions [23].

In summary, the use of refrigerants is always in constant change, with some of them being already banned or in phase of elimination. In Figure 2.24 it is possible to get a bigger picture of the used refrigerants nowadays, even though some of them have big GWP values or high flammability, because this depends on current legislation and equipment capacity, as its decline is a gradual process that can take many years.

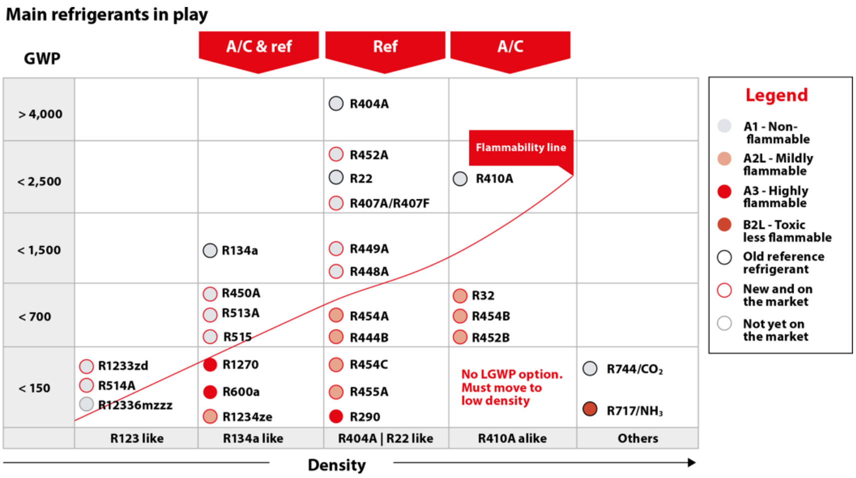


Figure 2.24: Main refrigerants at play currently [24].

2.7 Refrigeration Cycles

Refrigeration cycles are a process in thermal engineering that plays an important role in a variety of applications, including food preservation and medicine, air conditioning and industrial cooling. The basis of these cycles is the transfer of heat from a low-temperature zone to a high-temperature one, which is the opposite of the natural direction of heat flow, only being possible to accomplish by delivering external work to a compressor or a pump. There are various types of refrigeration cycles, with the vapor-compression cycle being the most common [25].

This section aims to explain the basis of a refrigeration cycle and to expose some of the refrigeration cycles that are used in the supermarket solutions that will be studied in detail later.

2.7.1 Basic Refrigeration Cycle

As shown in Figure 2.25, the compression process takes place from state 1 to 2 with external work entering the cycle. At this point, the superheated refrigerant vapor from state 1 enters the compressor, where the pressure, temperature, and energy of the vapor rapidly increase. Compression ends at state 2, and at this point the temperature and energy of refrigerant vapor have the highest value in the whole cycle.

The next evolution, from 2 to 3, represents the transition of the fluid in the condenser, cooling the superheated high-pressure vapor up to the point where it begins to condense until it reaches the liquid state (x=0). During this process, a lot of energy is rejected to the environment, that is at an inferior temperature than the condenser, in the form of heat (Q_h).

Now that the fluid was cooled, it is then expanded in the expansion valve, for its pressure to decrease (but also the temperature). The expansion process, from 3 to 4, is treated as an isenthalpic process, so the enthalpy of the refrigerant remains constant.

Finally there is the evaporation process, from 4 to 1, where the fluid receives heat, Q_e, from the space to be cooled and starts to evaporate at constant temperature and pressure. When all the liquid is evaporated, point 1 is reached, defining saturated refrigerant vapor (x = 1) and then the compression process starts over again [26].

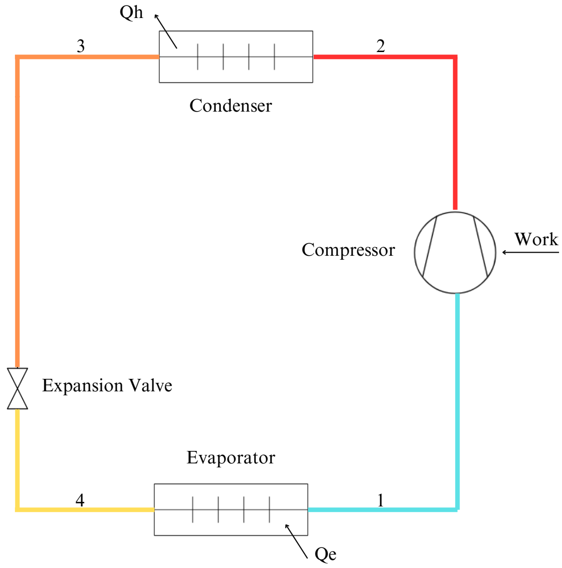


Figure 2.25: Basic refrigeration cycle.

Figure 2.26 represents this evolutions of state in a log(p)-h diagram for R290, the most popular refrigerant in stand-alone units nowadays, which have a simple refrigeration system.

At the entry of the expansion valve it is usually recommended to have liquid refrigerant, so a subcooling process takes place from point 3 to 3', at the exit of the condenser. Also, at the exit of the evaporator the vapor is superheated, goes from state 1 to state 1', to make sure that the refrigerant entering the compressor will not contain liquid; the presence of liquid at the compressor causes problems in the operation of the equipment. For this case, a heat exchanger is added to the cycle [26].

2.7.2 Cascade Refrigeration Cycle

The cascade refrigeration cycle consists in two independent refrigeration cycles that are connected through an intermediate heat exchanger. This heat exchanger works like a condenser for the Lower Temperature cycle and as the evaporator of the Medium Temperature cycle. Each cycle uses a different refrigerant, selected according to its characteristics for a specific temperature range. An example of a cascade refrigeration cycle can be seen in Figure 2.27.

The first cycle, known as the low-temperature (LT) cycle, is responsible for reaching the lowest temperatures and operates directly in the space to be cooled. The refrigerant in this cycle evaporates at low pressure and temperature, absorbing heat from the environment. After evaporation, the vapor is compressed and sent to the intermediate heat exchanger, where it condenses.

In this intermediate exchanger, the heat released by the LT refrigerant is absorbed by the refrigerant of the second loop, referred in some literature also as high temperature (HT) cycle. This two cycles operate as a conventional vapor-compression cycle.

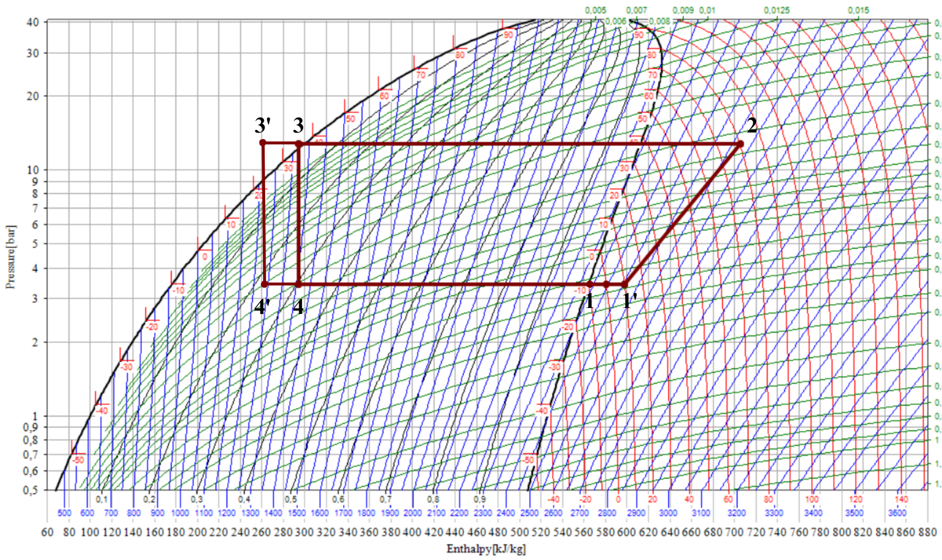


Figure 2.26: Diagram log(p)-h for R290 (adapted from *Pack Calculation Pro software*).

The main advantage of this cascade configuration is the ability to use refrigerants optimized for specific temperature ranges, avoiding excessive pressures. This approach significantly improves the system's performance and enables safe and reliable operation at ultra-low temperatures [27].

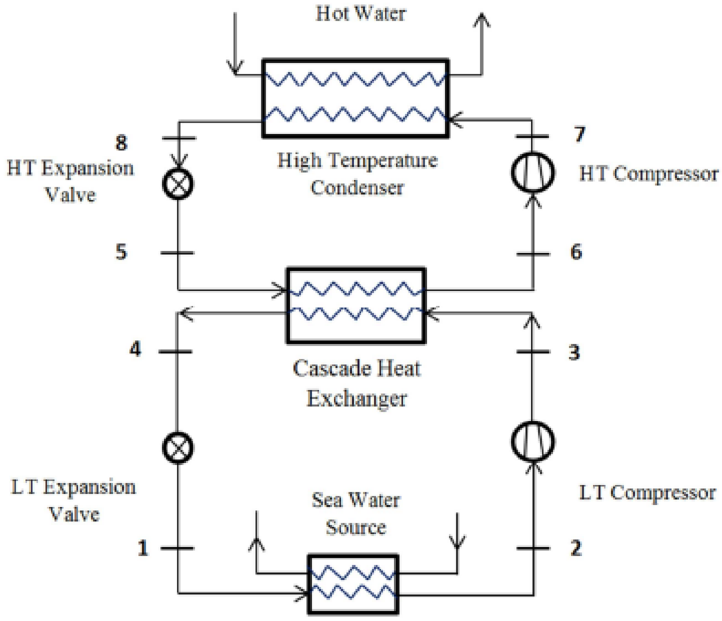


Figure 2.27: Cascade refrigeration cycle [27].

For the specific case going to be studied, the working fluids are going to be R744 operating in the subcritical regime for the LT cycle and R134a operating in the MT cycle. Figure 2.28 shows how log(p)-h diagrams behave for cascade cycles.

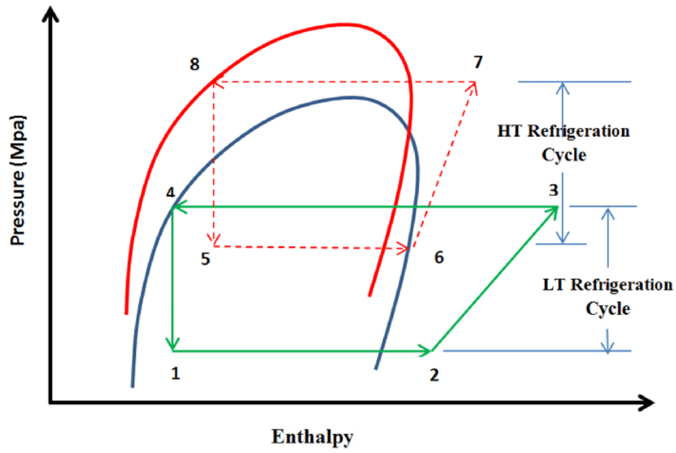


Figure 2.28: Example of a log(p)-h diagram for cascade cycles [27].

2.7.3 Two Stage Transcritical Cycle (CO_2 Booster)

A CO_2 booster refrigeration cycle is a two-stage vapor compression system commonly used in supermarkets with a central system solution or remote condensing units, as it was already mentioned in the last section. The working fluid for both LT and MT cycles is R744 due to it's special features (low critical point and high pressures).

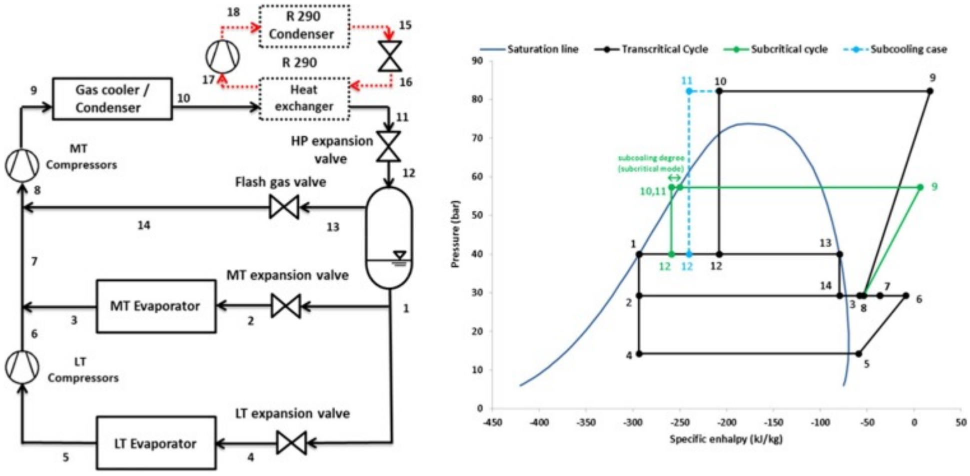
Resorting to Figure 2.29, in this system the evaporated refrigerant from the LT cycle (states 4 to 5), typically at very low temperatures like -35ºC, is first compressed by a set of LT compressors to an intermediate pressure (states 5 to 6). At the same time, the vapor from the MT evaporators that can be at -10ºC, for example (states 2 to 3), mixes with the LT compressed fluid to go into the set of MT compressors (states 8 to 9). After mixed, both vapor streams are compressed to the system's higher pressure. After achieving the highest pressure, CO_2 flows into a gas cooler. When operating with transcritical systems, the condenser is substituted by a gas cooler because the heat release occurs at ambient temperatures above the critical point of CO_2, where there is no phase change (remains in the gaseous state). In the gas cooler, heat is rejected to the environment but if the ambient temperature is low enough, the system can operate in subcritical mode, where the gas cooler behaves as a condenser.

In most CO_2 booster systems, after leaving the gas cooler and passing the expansion valve, there is a flash tank or receiver, used to separate the saturated liquid from the vapor after expansion. The separated vapor is then redirected back to the MT compressors to be compressed again, while the saturated liquid goes to the LT and MT evaporators [27].

Figure below shows how R744 behaves working in the subcritical regime (LT) and how it works in the transcritical regime (MT).

2.7.4 Two Stage Transcritical Cycle (CO_2 Booster) with parallel compression

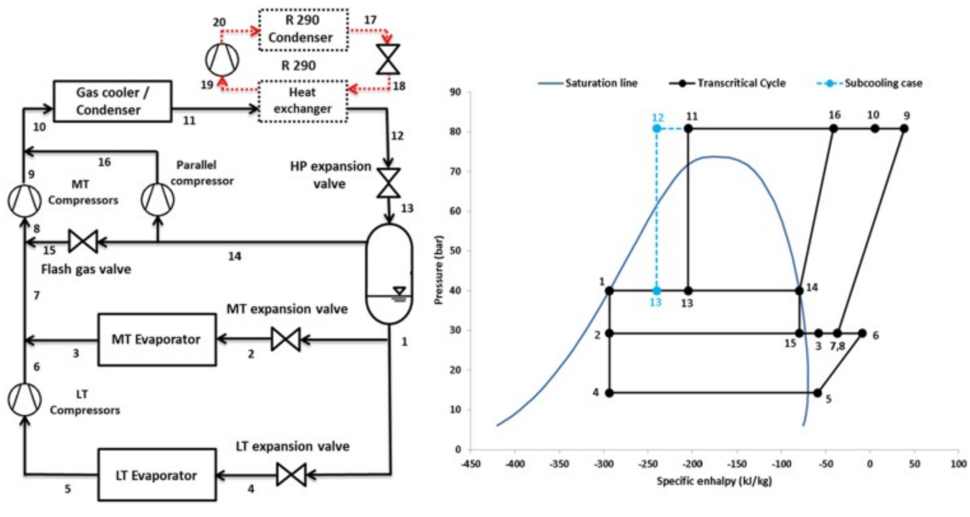
A variation for the CO_2 booster can be the addition to the system of a parallel compressor (Figure 2.30). This is the system used in portuguese supermarkets due to the high ambient temperatures



(a) (b)

Figure 2.29: CO_2 booster system. (a) The examined configuration. (b) The log(p)-h diagram [28].

detected for a certain period of months. When temperatures outside the supermarket are high, the refrigerant entering the liquid receiver has a higher vapor content (higher quality, x), which results in a greater amount of vapor needing to be compressed by the Medium Temperature (MT) compressors. To reduce the potential high energy consumption from the compressors, an auxiliary compressor is introduced, being responsible for compressing the vapor from the liquid receiver starting at the intermediate pressure level and raising it to the system's high pressure, which results in a higher energy efficiency. Figure below shows the log(p)-h diagram for this configuration [27].



(a) (b)

Figure 2.30: CO_2 booster system with parallel compression. (a) The examined configuration. (b) The log(p)-h diagram [28].

Chapter 3

Characterization of the Supermarkets

Three supermarkets were selected for analysis, in a specific area, representing three different types of refrigeration solutions that can exist, which are:

- Sales area with only stand-alone/plug-in units and cold storage rooms refrigerated by remote condensing units. In other way, a small store with a decentralized solution (Supermarket A);
- Central system using a transcritical CO_2 refrigeration system and some plug-in display cabinets (Supermarket B);
- Central system with a cascade refrigeration cycle using CO_2 and an HFC refrigerant and also some plug-in display cabinets (Supermarket C).

The chosen area is restricted to the northern coast of Portugal, with the objective of having similar average daily temperatures and establishing more accurate comparisons between temperature and energy consumption.

A centralized control system that can monitor, regulate, and automate the functioning of all refrigeration components, such as compressors, expansion valves, fans, condensers, evaporators, and sensors, must be installed in every installation. These systems save the data obtained for further studies while continuously monitoring vital parameters including temperature, pressure or energy consumption. Centralized control systems can also use optimization algorithms to lower overall energy usage through preventative maintenance procedures like heat recovery, peak load management, and circuit performance comparison to find inefficiencies.

In this section, supermarkets A, B and C will be analyzed in detail. Firstly, a contextualization of the stores will be made, with the presentation of the floor plan that was studied and the respective locations of the display cabinets, ice machine and cold storage rooms. After this contextualization, the next step will be to analyze the theoretical maximum energy consumption (for the case there is lack of actual data for the energy analysis), the refrigerant charge and the TDA of all display cabinets and ice machines, using supplier catalogs, as well as for the evaporators in cold storage rooms and for the RCUs. The refrigerant charge may be present in catalogs or in the design details and the theoretical energy consumption is considered to be the theoretical maximum energy required for a system when it is working at maximum design conditions (full capacity).

Having all the information gathered about the parameters necessary to calculate TEWI, it will be time to analyze and compare how the different system solutions respond to ambient temperature variations as a function of time, using for this the real data obtained trough the systems' controllers (but also theoretical maximum energy consumptions calculated in case of need). The objective is to verify the hypothesis that a central system can control better its consumptions, being more energy efficient than a built-in unit, also because built-in units release energy at the same temperature range into the store all year round, +20/+25 ºC.

The next step will be to obtain data on the annual leakage rates for the different supermarkets, by consulting the After-Sales Department and getting to know what the typical operational lifespan of a system is.

Finally, once all the necessary values and data have been collected, it will be possible to calculate the installations' TEWI and establish metrics for comparison such as TEWI/TDA for display cabinets and TEWI/Vol for cold storage rooms.

At the end of the analysis of all supermarkets, the investment and maintenance costs will also be taken into account with the TEWI of each facility. As a note, for all the stores studied the climate class is 3 (dry bulb temperature equal to 25ºC and relative humidity is 60%) and the maximum design temperature is 32ºC.

3.1 Supermarket A

This will be the example explained in more detail, with all calculations and considerations presented. This store, installed in 2023, is equipped with just plug-in display cabinets inside the sales area, where the heat from the refrigeration cycle is dissipated and has a remote system with RCUs for the cold storage rooms, which are placed inside the supermarket but hidden from the view of customers, since for this type of smaller stores it is not worth having centralized systems; the store has a ground floor, where the refrigeration equipment is located and the RCUs are located in the upper floor, releasing the heat from the gas cooler to the environment. The areas of interest studied (zone of cold storage rooms and display cabinets) can be found in Appendix A; the nomenclatures utilized for display cabinets and cold storage rooms are according to the designations given on each layout and vary from store to store.

For this refrigeration installation, a direct expansion system was used, the most widespread in centralized and decentralized systems, where the primary refrigerant is circulated directly to the evaporators located in the cold storage rooms.

3.1.1 Cold Storage Rooms (CSR)

For this store, there are four cold storage rooms: one for frozen products (CC01), two for chilled products, (CR01 for various products and CR02 for fresh fish) and one climatized room for garbage

(CL01). The evaporators are located inside the storage rooms that are connected through a piping system to the RCUs, which contain the compressors and gas coolers. The chilled storage rooms are connected to UC02 as seen in Figure 3.1. It is important to notice that all evaporators in this installation will have to be prepared to work with pressures of 80 bar. CR01 is connected to remote condensing unit UC01, as suggested in Figure 3.2.

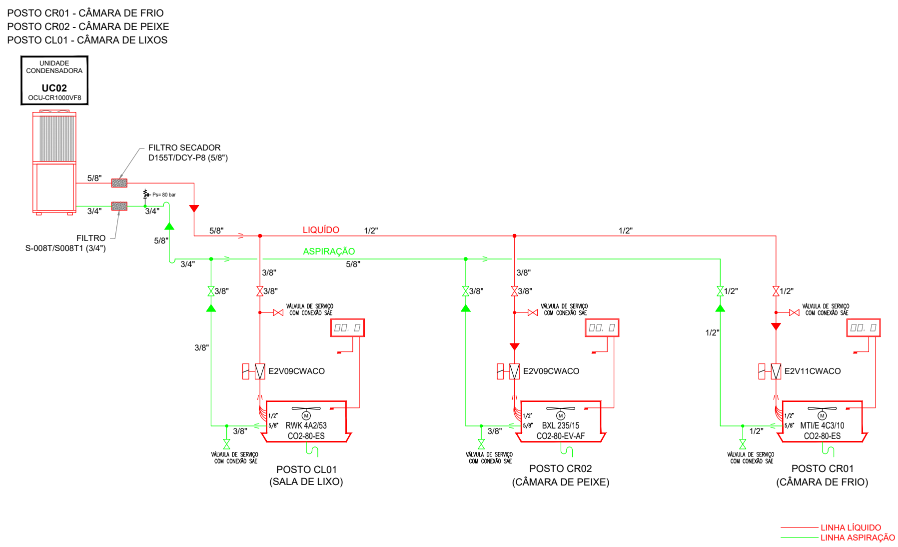


Figure 3.1: Circuit for chilled storage rooms. UC02 is connected to three evaporators.

Some of the most important technical parameters from the evaporators for this study were took from Supplier A catalogs and are discriminated in Table 3.1, below. It is possible to see that the defrost is of electrical type and the power needed for this process is expressed for each fan. The fans and defrost heaters of evaporators are considered ancillary components, so their accounting is separate from RCUs.

Table 3.1: Technical data of cold room evaporators for Supermarket A.

Cold Storage Rooms	CC01	CR01	CR02	CL01
Refrigeration Temperature	Negative	Positive	Positive	Positive
Evaporator Model	DDI/E 7G3/77 CO2-80-EC-RG	MTI/E 4C3/10 CO2-80-ES	BXL 235/15 CO2-80-EV-AF	RWK 4A2/53 CO2-80-ES
Cooling Capacity [kW]	8	6.3	3.5	3.5
Room Temperature [ºC]	-20	0	0	3.5
Evaporation Temperature [ºC]	-25	-6	-5	-6
Relative Humidity [%]	95	80	80	80
Room Volume [m^3]	94.71	64.59	29.52	32.19
Fan Motors				
Quantity	3	3	2	2
Absorbed Power per Fan [W]	400	34	140	35
Defrost (Electrical Type)				
Absorbed Power [kW]	10.8	6.48	2.16	-
DEC [kWh/24h]	37.80	4.46	4.44	0.84

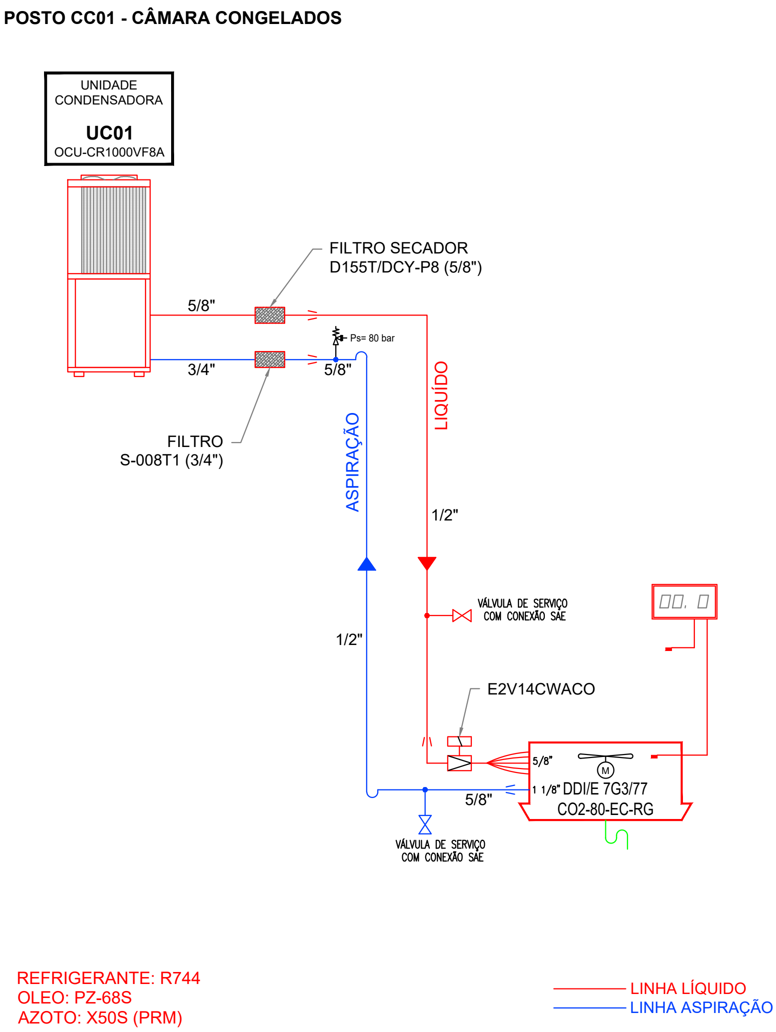


Figure 3.2: Frozen storage chamber circuit, CC01.

3.1.1.1 Defrosting in cold storage rooms

To calculate energy consumption in cold storage rooms, the energy for the evaporators during their operating periods is taken into account, as well as the defrost power and its defrosting time. Only when all these considerations are known it will be possible to calculate the respective share of energy consumption. Furthermore, it is important to acknowledge that display cabinets also have anti-sweat heaters and illumination needs, but those will not be considered in later calculations due to lack of information and the power required being substantially lower than the power required for electrical defrosting.

As data from technical sheets and suppliers on the defrosting process are sparse or sometimes, difficult to access freely, every time there is no data available, Table 3.2 will serve as a guide for all considerations made in this study regarding the number of defrosting operations performed per day and their duration, in function of its operating temperature, since the table is based on values commonly found in the refrigeration industry.

Table 3.2: Defrosting time according to room temperature.

Room temperature [ºC]	Number of cycles/day	Defrost time/cycle [min]	Defrost time/day [min]
+2	1	10	10
0	2	15	30
-5	2	20	40
-10	2	25	50
-20	3	30	90
-30	4	30	120

Normally, above +2ºC there is no large energy consumption from defrost cycles and for this reason it will not be counted (as for CL01 in Table 3.1). For cold rooms containing frozen products, it is also important to take into account the formation of ice on the door and on the sewage pipe inside the room and the consequent existence of electrical resistances in these regions. For the door, a required power of 20W/m will be considered and it is assumed that the door is 2 meters long and 1 meter wide, therefore a perimeter of 5 m, so, a total power of 100 W. For the sewage pipe it is considered that 2 meters of it are inside the room and the required power is 20W/m, therefore a total of 40 W.

Still in the field of considerations, it will be assumed that the frozen chamber will operate 18 hours a day and the chilled chambers operate 12 hours a day, since once the desired climatic conditions are reached there is no need to have compressors and evaporators working 24 hours a day.

3.1.1.2 Calculation of recommended refrigerant charge

Part of the Supermarket A store layout, more precisely, for the location of the RCUs, is shown in Figures 3.3 and 3.4, where it can be seen that the RCUs are located at the rooftop of the building. These are important to understand and to calculate the recommended refrigerant charge to put on the circuit, which can be obtained using *Panasonic PRO Club*, a free online platform created for HVAC&R professionals, that includes tools such as a *Sizing and Simulation* software. For these calculations, it is necessary the evaporators' data from the table above and to measure the length of one of the piping lines (it can be the liquid or suction line).

The way how to calculate, with all the steps, the refrigerant charge of the installation using *Panasonic PRO Club software* can be consulted in Appendix B.

The data from the RCU's used in this project is summarized in Table 3.3, already containing the refrigerant charges, which are close to the typical values (1 - 10 kg).

For the theoretical energy consumption calculations, it was then considered that the RCUs also work 18h a day and 12h a day as already mentioned for evaporators, for frozen or refrigerated operations, respectively, and the defrosting times according to the working temperatures on Table 3.2. Summing up the supplied power for evaporators, defrost of rooms, doors and sewing pipes, the total theoretical energy supplied would be 70.88 kWh/24h and the total cold rooms' volume is 221.01 m^3 (maximum energy the system would require if the outside temperature is the design

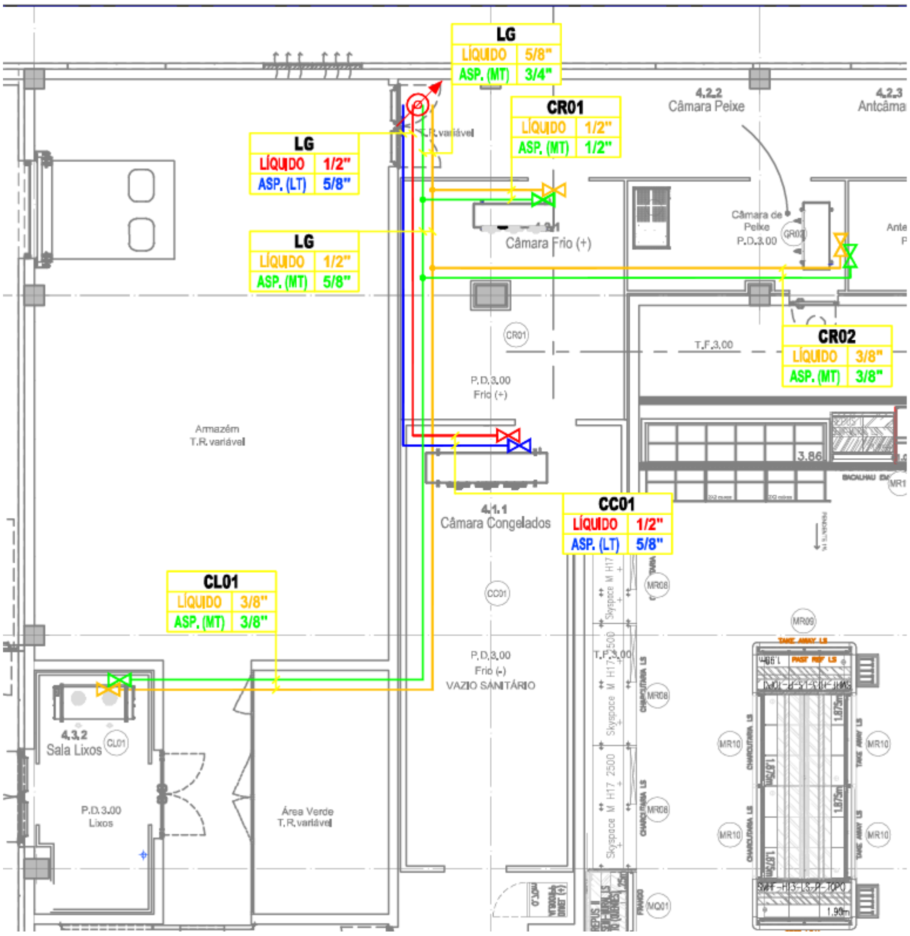


Figure 3.3: Piping system for cold storage rooms on the ground floor.

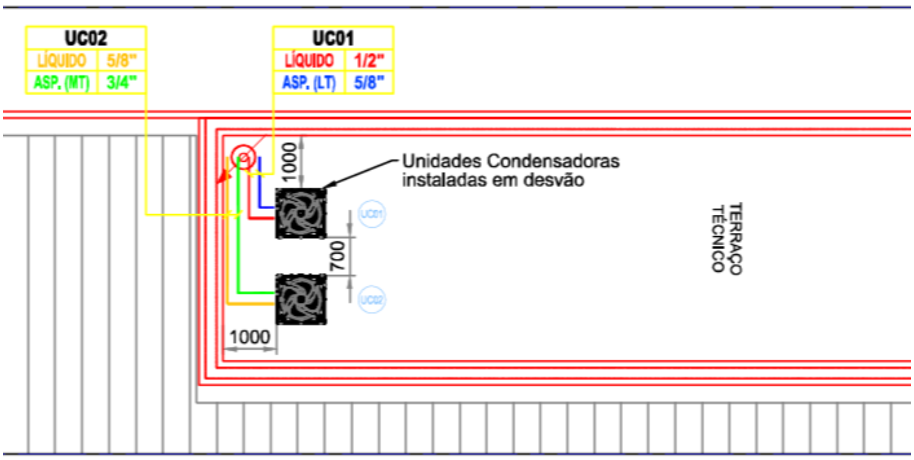


Figure 3.4: Connection of RCUs with the piping system on the first floor.

Table 3.3: Remote Condensing Units' Data.

Remote Condensing Units	UC01	UC02
Brand	Panasonic	Panasonic
Model	OCU-CR1000VF8A	OCU-CR1000VF8
Standard Ambient Temperature [ºC]	32	32
Evaporation Temperature [ºC]	-35	-10
Power Consumption [kW]	7.57	8.2
Cooling Capacity [kW]	8	14
Recomended Refrigerant Charge [kg]	12.2	12.3

one, 32ºC). For RCUs, they are responsible for 24.5 kg of R744 refrigerant in the system and 234.66 kWh/24h.

3.1.2 Ice Machine

By principle, every supermarket has an ice machine in the same space as the cold room where fresh fish is stored, as it is more practical, like it is shown in Figure 3.5. Since this store is designed with RCUs and plug-in units, the ice machine is also a plug-in unit, being connected directly to the power grid. It was considered that for supermarkets, ice machines work 8 hours per day.

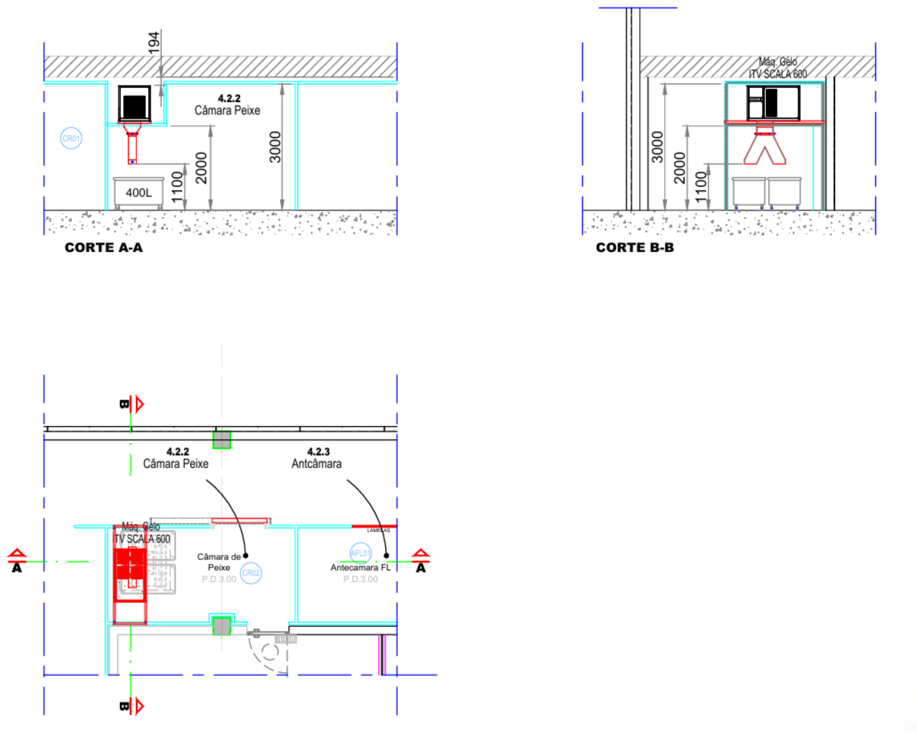


Figure 3.5: Location and positioning of the ice machine.

The ice machine is the model *Scala 600 Split* from *ITV-Ice Makers* company and uses R449A, as it can be seen in Figure 3.6, so when analyzing the catalog available online, the most important things to know for the evaluation of electrical consumption and later, the TEWI, are the refrigerant used and the compressor power, which is 190 W. The energy consumption, assuming that it works height hours per day (during night), is 4.56 kWh/24h and refrigerant charge is 0.15 kg, the limit value by legislation, considered every time when nothing is said about refrigerant charge.

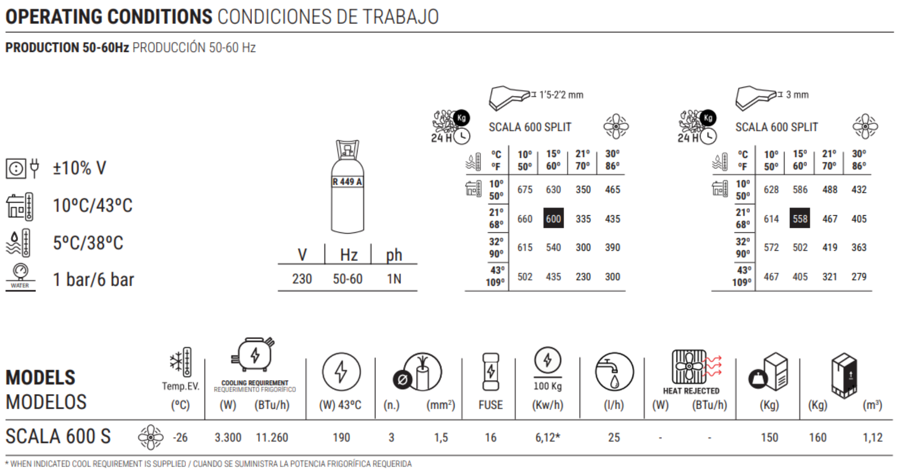


Figure 3.6: Ice machine details of Supermarket A.

3.1.3 Plug-in Display Cabinets

Before any analysis, Figure 3.7 helps to remind and explain how energy consumption works in display cabinets. How it can be seen in the figure, if having plug-in units, energy is given by TEC, but if having remote display cabinets, connected to a centralized system, TEC splits into DEC and REC.

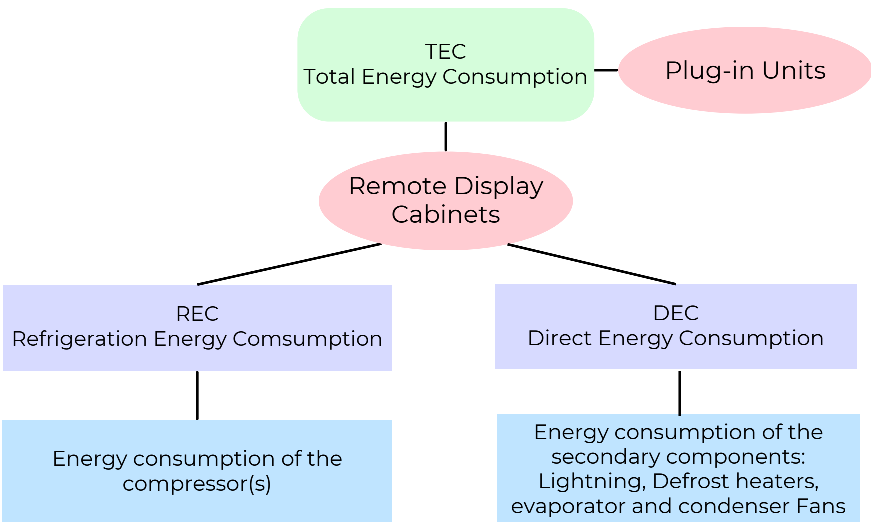


Figure 3.7: TEC for Plug-in units and remote display cabinets.

TDA, refrigerant charge and theoretical daily consumptions of the plug-in display cabinets were determined by first analyzing the floor plan to identify all existing cabinets, and then gathering as much information as possible from catalogs and supplier websites to ensure the study closely reflected real conditions.

When talking about plug-in display cabinets, as it was mentioned in Chapter 2, the DEC equals the Total Electrical Consumption (TEC), because the condensing unit is already incorporated in the equipment. Also, the defrosting operation is automatic, which means that the equipment itself is capable of managing and executing defrost cycles autonomously, so there is no need to account them in this cases; as these catalogs usually give information about daily consumption, there is also no need to account lightning.

All plug-in units use R290 as working fluid. Table 3.4 expresses all the frozen display cabinets, their model, existing quantity in the store, charge of refrigerant, TDA, net volume, length of the cabinet and maximum energy consumption.

Table 3.4: Frozen display cabinets of Supermarket A.

Frozen Display Cabinets	MC01	MC02	MC03	MC04
Model	PARIS	PARIS	EYRIS + SOUND TOP	MINI ASTANA
Quantity	4	8	2	2
Used Refrigerant	R290	R290	R290	R290
Refrigerant Charge per cabinet [kg]	0.11	0.12	0.13+0.15	0.15
TDA per cabinet [m^2]	1.02	1.27	1.87+1.68	5.9
Net Volume [liters]	568	660	794+760	1383
Length [mm]	1854	2102	2500	2343
Energy Consumption				
DEC [kWh/24h]	15.36	33.52	50.00	10.72

In some cases there was no manner of knowing the refrigerant charge so it was considered the maximum allowed by law, 0.15 kg. Therefore, the total maximum daily energy consumption is equal to 109.6 KWh/24h, the refrigerant charge is 2.26 kg and the TDA is going to be 33.14 m^2.

Often there was no direct information about TDA, so there is an example, below, how TDA was calculated for IP01, based on Figure 3.8 (according to EUROVENT Guides).

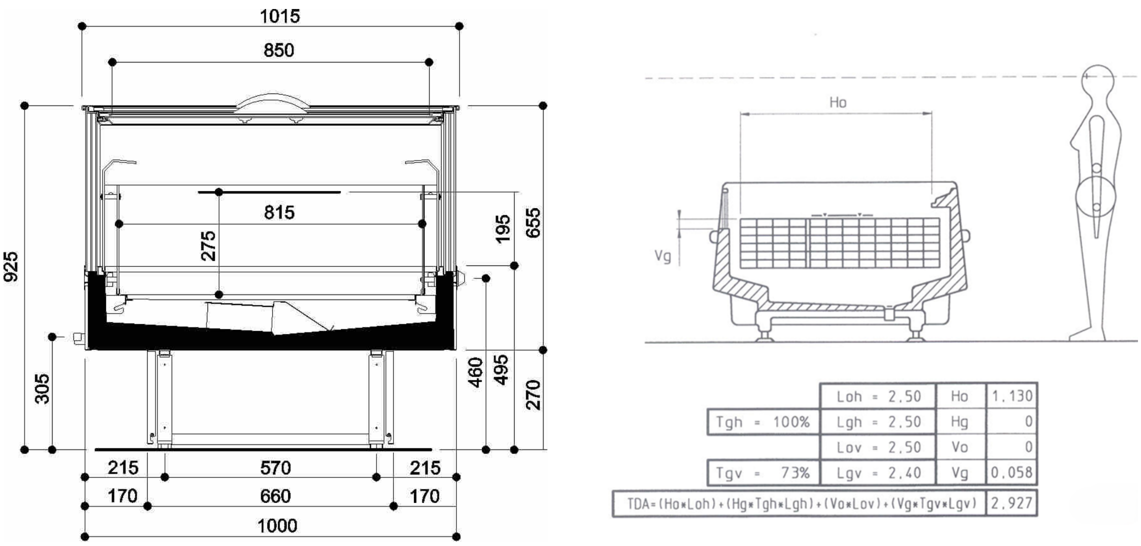


Figure 3.8: Example for calculation of TDA.

Ho is equal to 815 mm and Vg to 275 mm; Lo = 2000 mm, Lv = 1900 mm and there are five surfaces exposed to customers on this display cabinet. Considering that the lateral glasses have a light transmission through the glazing surface of 73%,

$$TDA = (H_o \times L_{oh}) + (H_g \times T_{gh} \times L_{gh}) + (V_o \times L_{ov}) + (V_g \times T_{gv} \times L_{gv}) =$$

$$= 815 \cdot 2000 + 0 + 0 + 2 \cdot 0.73 \cdot (275 \cdot 1900 + 275 \cdot 815) = 2.62 m^2 \quad (3.1)$$

Which is very similar to 2.57 m^2, value taken from the catalog.

The same is done for another promotional islands and chilled display cabinets, respectively in Tables 3.5, 3.6 and 3.7.

Table 3.5: Promotional Islands of Supermarket A.

Promotional Islands	IP01	IP02	IP03	Fish Counter	Butchery Counter
Model	Captur	Expo	Captur	Expo	Expo
Quantity	1	1	1	1	1
Refrigerant Max. Charge [kg]	0.15	0.15	0.15	0.15	0.15
TDA [m^2]	2.57	1.75	2.57	1.75	1.75
Net Volume [liters]	423	-	423	-	-
Length (mm)	2000	1500	2000	1500	1500
Energy consumption					
DEC [kWh/24h]	16.40	32.52	16.40	32.52	32.52

So, for this set the nominal daily energy consumption is equal to 130.36 kWh/day, the refrigerant charge is 0.75 kg and the TDA is going to be 10.39 m^2.

Table 3.6: Chilled display cabinets of Supermarket A (a).

Chilled Disp. Cabinets	MR01	MR02	MR03	MR04	MR05	MR06
Model	Proxima Efficia	Osaka 3P	Osaka 2	Osaka 2	Panama 3P	Panama 3P
Quantity	2+1	1	1	2	1	1
Refrigerant Charge [kg]	0.45	0.15	0.15	0.30	0.15	0.15
TDA [m^2]	6.16+4.11	2.10	3.65	10.94	3.32	4.70
Length [mm]	1875+2500	1250	2500	3750	1975	2500
Energy consumption						
DEC [kWh/24h]	10.73	1.39	2.18	5.57	1.39	2.74

The balance for the chilled display cabinets indicates that the total refrigerant charge is 3 kg, the total daily consumption is 246.50 kWh/24h and the sum of all TDA's is 64.47 m^2. Table 3.8 shows, in a summarized way the theoretical energy consumption, total room volume, TDA and refrigerant charge of the equipments analyzed above.

Table 3.7: Chilled display cabinets of Supermarket A (b).

Chilled Disp. Cabinets	MR07	MR08	MR09	MR10	MR11
Model	Osaka 2	Skyspace M	SMHF-H13-TOPO	SMHF-H13	Repus II
Quantity	1	3	2	4	1
Refrigerant Charge [kg]	0.15	0.45	0.3	0.6	0.15
TDA [m^2]	2.88	10.77	4.82	9.48	1.55
Length [mm]	2500	2500	1900	1875	1250
Energy consumption					
DEC [kWh/24h]	2.09	4.11	64.27	126.72	25.32

Table 3.8: Summary table with the important parameters to calculate the TEWI of Supermarket A.

Parameters	PI (R290)	Chilled Units (R290)	Frozen Units (R290)	Ice Machine (R449A)	CSR (R744)	Ancillary Components + Plug-in Units	RCU (R744)
Theoretical Energy Consumption [kWh/24h]	130.36	246.50	109.60	1.52	70.88	558.86	234.66
Total Room Volume [m^3]	-	-	-	-	221.01	221.01	-
TDA [m^2]	10.39	64.47	33.14	-	-	108.00	-
Refrigerant charge [kg]	0.75	3.00	2.26	0.15	-	6.01	24.5

3.2 Supermarket B

Supermarket B is a larger store than the previous one, so the type of refrigeration system used is a central system installed in 2019 and working with a transcritical CO_2 refrigeration cycle, where the rack of compressors is placed outside the store to avoid noise issues and the gas cooler stays in the rooftop. The central system is constituted by a piping network that connects the cold storage rooms, display cabinets, rack of compressors and gas cooler. For the low temperature cycle, where the rooms and display cabinets with negative temperatures are refrigerated, the LT compressors only work with CO_2 in its subcritical state; for the medium temperature refrigeration cycle (positive temperature equipments), there are MT compressors that can both work with CO_2 in its subcritical or transcritical state, depending on the outside temperature. There are also some stand-alone units inside the store which use R290. The areas of interest of the store can be seen in Appendix A.

3.2.1 Units Connected to Central System

All cold storage rooms and most of the display cabinets are connected to a central system working with CO_2, which makes it more easy to get to know the charge of refrigerant that flows trough the piping network that connects all these equipment. In the supermarket construction project, the transcritical diagram description indicates that the refrigerant capacity of the installation is 150 kg (which is between the indicated interval for centralized systems of 20-300 kg). It is also important to remind that, for the display cabinets and cold storage rooms connected to the central system, only the evaporators and defrost heaters are inside them.

3.2.1.1 Compressors

Figure 3.9 shows the transcritical diagram of the installation, with the respective compressors, valves and receiver used and Figure 3.10 show the compressors in more detail.

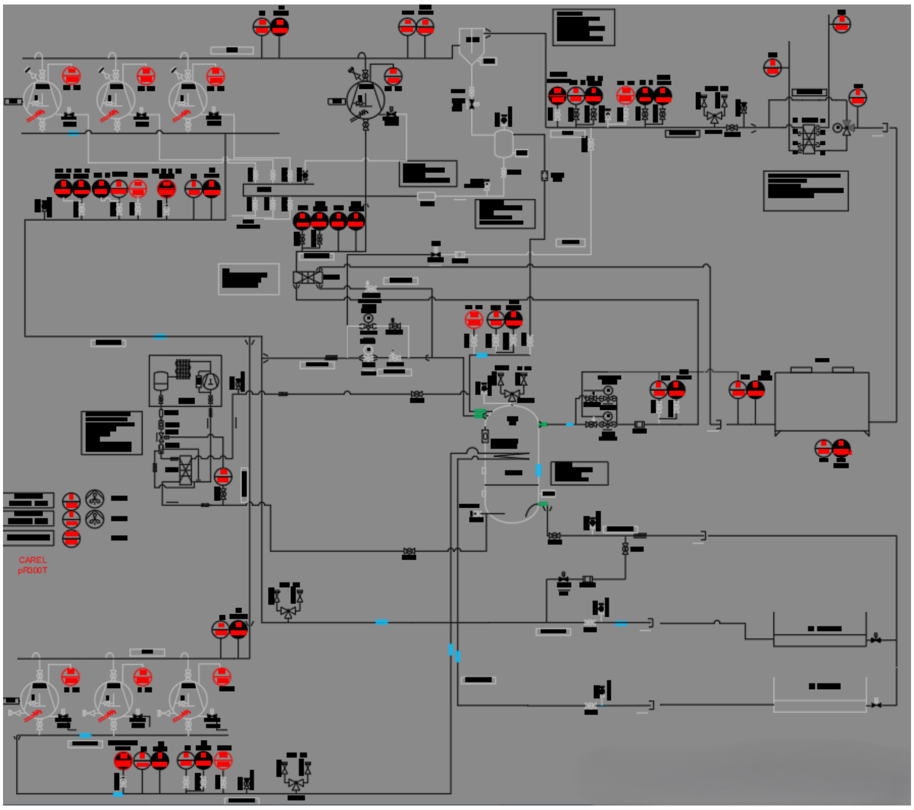
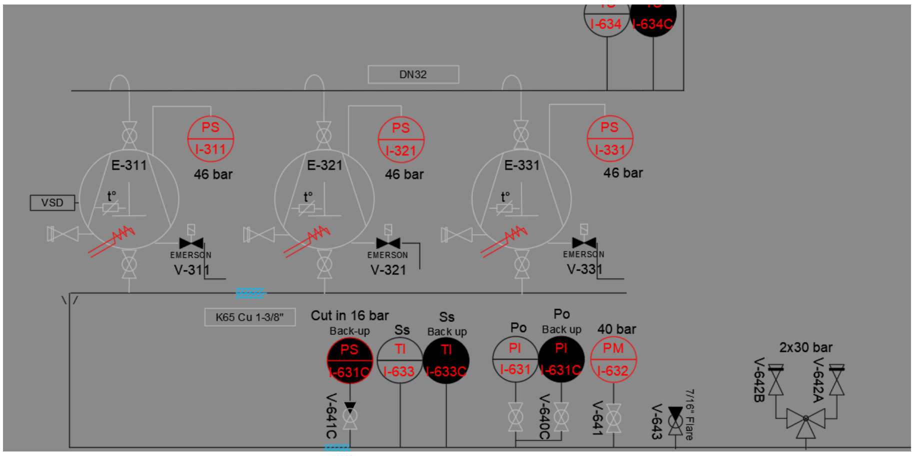
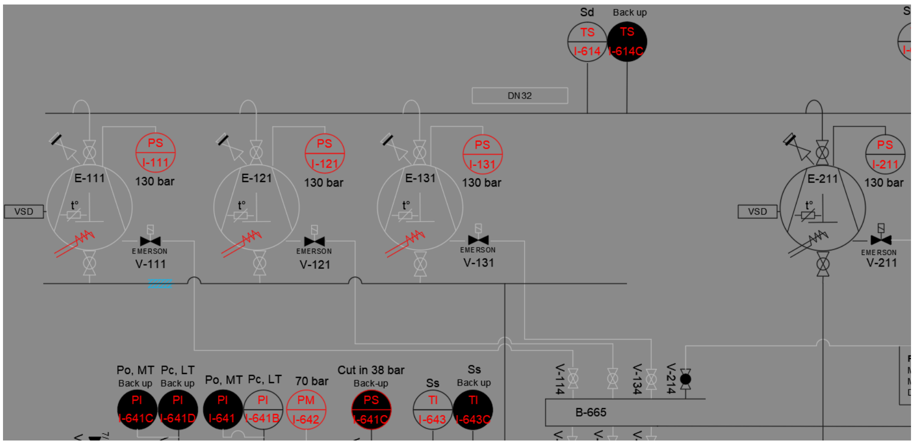


Figure 3.9: CO_2 transcritical diagram of the central system.



(a)



(b)

Figure 3.10: Installation's compressors in detail. (a) Low temperature compressors (E-311, E-321 and E-331). (b) Medium and high temperature compressors and parallel compressor (E-111, E-121, E-131 and E-211).

Compressors do not always work all at the same time, as their operation is modulated according to the cooling needs at that time, which depend intrinsically on the external temperature; Normally, only in summer, when temperatures are very high, it can happen that all compressors are working. The compressors selected for this project were found in the project's bill of materials and are as follows:

- E-111 and E-121: Compressor Bitzer 4HTC-20K, R744, 50Hz;
- E-131: Compressor Bitzer 4FTC-20K, R744, 50Hz;
- E-311 and E-321: Compressor Bitzer 2KSL-1K, R744, 50Hz;
- E-331: Compressor Bitzer 2JSL-2K, R744, 50Hz;
- E-211: Compressor Bitzer 4JTC-15K, R744, 50 Hz. Parallel compressor, only used in emergency situations or in very hot days.

This information is going to be useful when analyzing the energy consumption of this supermarket and to establish an annual load model, reminding that when having a centralized system, electrical consumption splits into REC and DEC.

3.2.1.2 Gas Cooler and Cold Storage Rooms

The gas cooler is a model *GCT-ACJ/EA 491/850 AR CE* with four fans from Supplier A. A scheme for the gas cooler can be seen in Figure 3.11. Considering that this gas cooler works 15 hours a day (not uninterrupted), its nominal consumption can be assumed has 24 kWh/day. Also the ice machine is a RHV 800 CO_2, with a consumption power of 280 W.

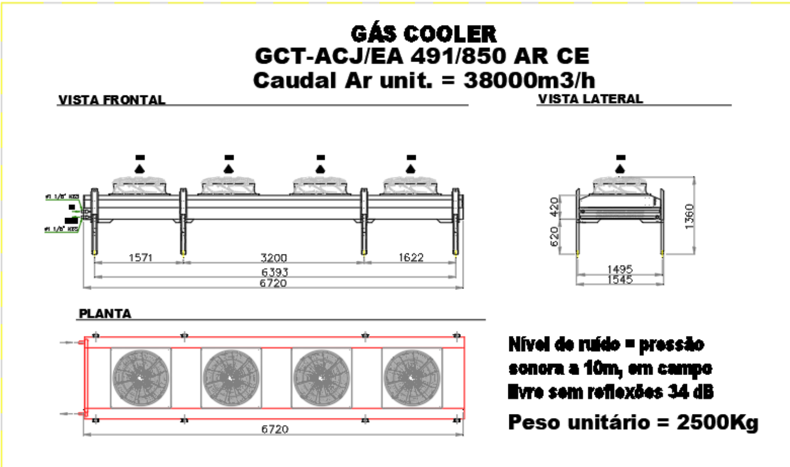


Figure 3.11: Gas cooler of the installation.

This supermarket contains 13 cold storage rooms, with two of them using gravity coils, which work by natural convection, so no electricity is consumed. Again, considering the working time and defrost time for each room according to their working temperatures, the nominal electrical consumption is 20.32 kWh/day, reminding that for this specific case, this value does respect to total power of fans and defrost heaters. Summing it with the ice machine and gas cooler values, electrical consumption is going to be 46.56 kWh/24h. The total room volume is 416.6 m^3. All tables with technical data on evaporators and refrigerated display cabinets can be found in Appendix C.

3.2.1.3 Display cabinets connect to the central system

The type of defrost for this cabinets can be of electrical or natural type, according to their working temperature. For cabinets working at 0/+2ºC, cabinets' technical sheets suggest a natural defrosting and their own defrost times, that means, the defrost is made by the fans instead of defrost heaters.

The TDA was calculated for all the display cabinets on Figure 3.12, and the sum of all TDA's is 113.77 m^2. Maximum energy consumption is 85.58 kWh/24h.

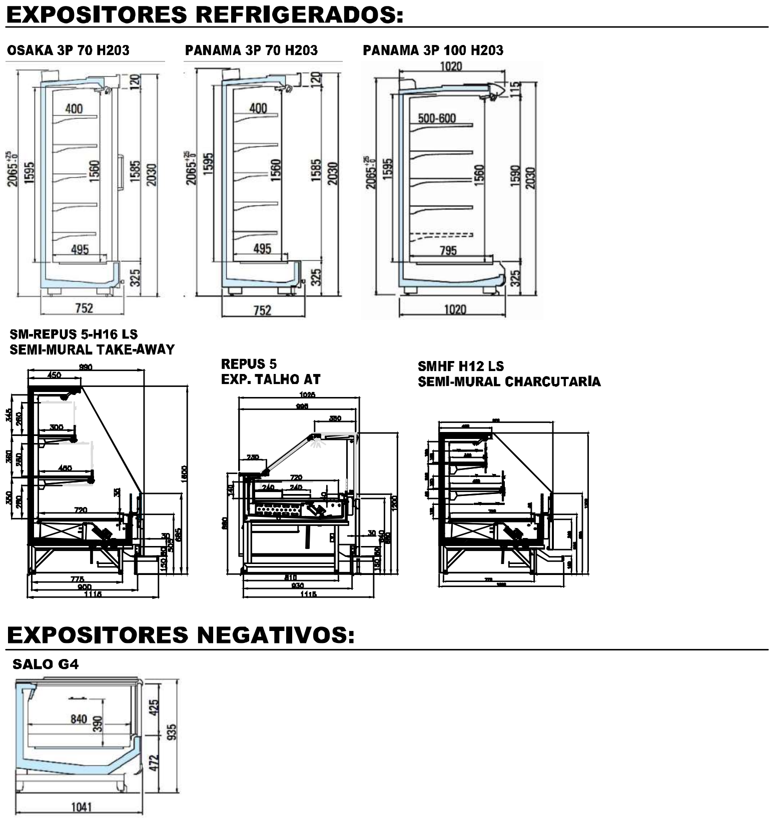


Figure 3.12: Display cabinets of Supermarket B.

3.2.2 Stand-alone Units

The plug-in units used are presented in Figure 3.13, which are similar to the ones in Supermarket A. For this set, the total TDA is 44.88 m^2, the refrigerant charge is 4.05 kg and the TEC is 315.91 kWh/24h.

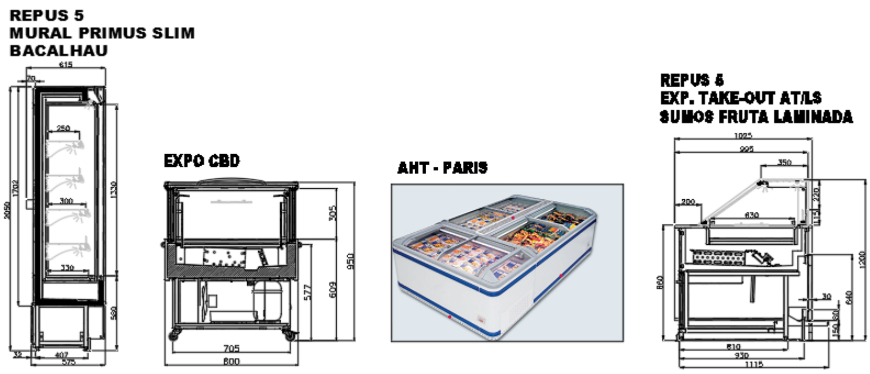


Figure 3.13: Plug-in units for Supermarket B supermarket.

The summary of the characterization of the parameters necessary to calculate the TEWI of the Supermarket B is given by Table 3.9. DEC of all auxiliary components is the sum of energy consumption of remote display cabinets, cold storage rooms, ice machine and gas cooler fans and defrost heaters.

Table 3.9: Summary table with the important parameters to calculate the TEWI of this installation.

Parameters	Plug-in Units (R290)	Remote Display Cabinets (R744)	CSR (R744)	Ice Machine + Gas Cooler	Total DEC + Plug-in units
Theoretical Energy Consumption [kWh/24h]	315.91	85.58	22.56	26.24	426.29
Total Room Volume [m^3]	-	-	416.60	-	416.60
TDA [m^2]	44.88	113.77	-	-	158.65
Refrigerant Charge [kg]	4.05		150.00		-

3.3 Supermarket C

Supermarket C has a centralized solution installed in 2016 which functions with a cascade system. The LT cycle works with a subcritical CO_2 refrigeration cycle and the MT cycle works with R134a. The rack of compressors is placed on the machine room that locates on the -1 floor and condenser is placed at the rooftop. This central system is responsible to refrigerate all the cold storage rooms and almost all the display cabinets, having just a few plug-in units using R290. The layout of the supermarket can be seen in Appendix A.

3.3.1 Units Connected to CO_2 and R134a Central Systems

On this specific case, R744 usually enters the heat exchanger with a temperature of -5ºC. R134a enters the heat exchanger with an evaporation temperature of -10ºC, receiving heat from the R744 refrigerant. Project conditions indicate that the refrigerant charge for R134a cycle introduced in the installation was 300 kg and the refrigerant charge of R744 was 170 kg. Diagrams for each cycle are going to be showed next.

3.3.1.1 Compressors and Condenser

Figure 3.14 represents the low temperature cycle with its network of pipes, receivers and three compressors, which are connected to a heat exchanger, also connected to the R134a cycle, responsible for the MT equipments and represented in Figure 3.15. In turn, MT cycle has four compressors that are connected to the condenser, where the heat is released to the environment.

The type of compressors chosen for the R744 cycle were Bitzer 2FSL-4K, R744, 50 Hz. For R134a cycle, project details indicate that compressors are from Copeland brand, being one compressor from the model Copeland 4ML-15X, R134a, 50 Hz and the other three from the model Copeland 4MU-25X, R134a, 50 Hz.

Condenser's model is expressed in Figure 3.16 is *GCT-ACPD/EA 880/658 EC* with eight fans from Supplier A. Considering that this condenser works 15 hours a day (not uninterrupted), its theoretical consumption for the fans can be assumed has 37.2 kWh/24h. Also the ice machine is a RHV 800 CO2, with a consumption power of 280 W.

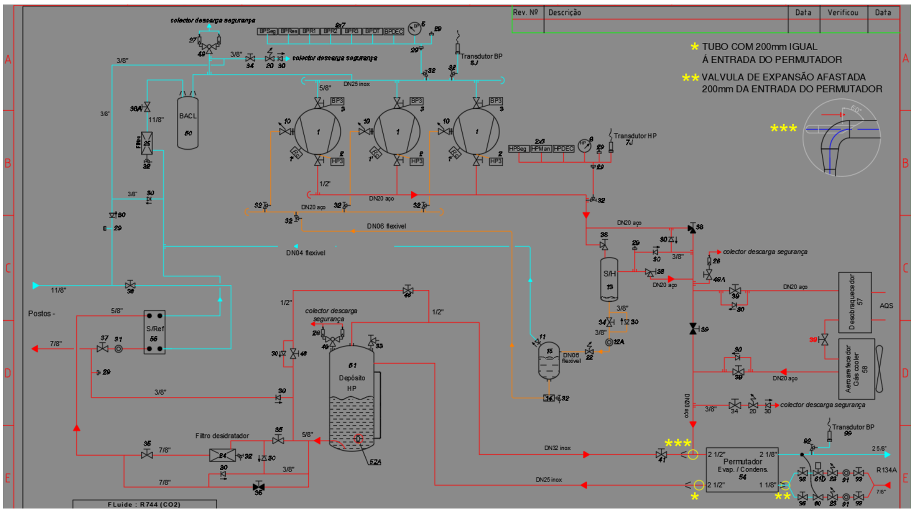


Figure 3.14: Installation's compressors in detail, R744 diagram with three compressors, LT cycle.

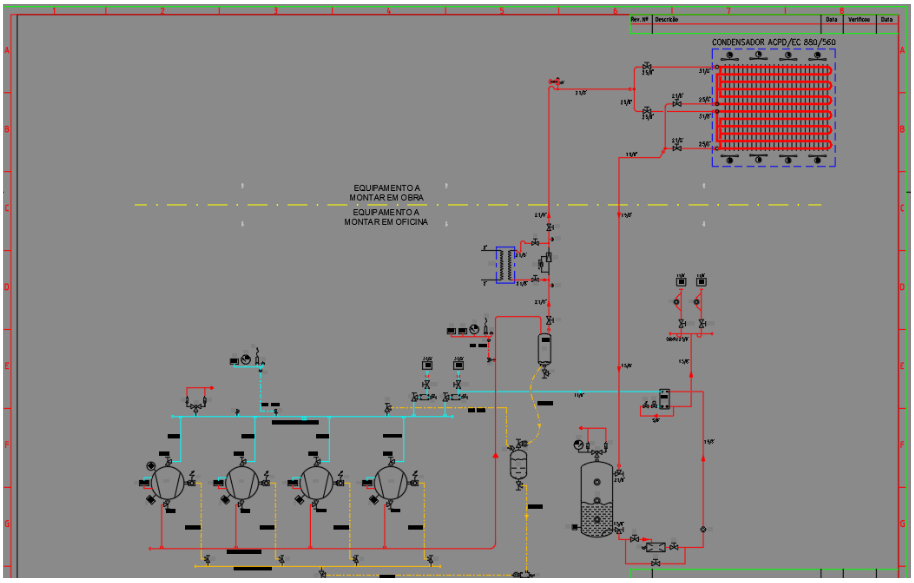


Figure 3.15: Installation's compressors in detail, R134a diagram with four compressors connected to the condenser, MT cycle.

3.3.1.2 Cold Storage Rooms

This supermarket only has two storage rooms for frozen products but has seven acclimatized or chilled storage rooms. Technical data for all evaporators, refrigerated display cabinets and stand-alone units is present in Appendix C.

The theoretical energy consumption of the ancillary components for the cold storage rooms is going to be the sum of all energy used to supply fans and defrost heaters on the two central systems, so, adding that to the condensers fans and ice machine, this gives a value of 62.94 kWh/24h and their total room volume is equal to 194.33 m^3.

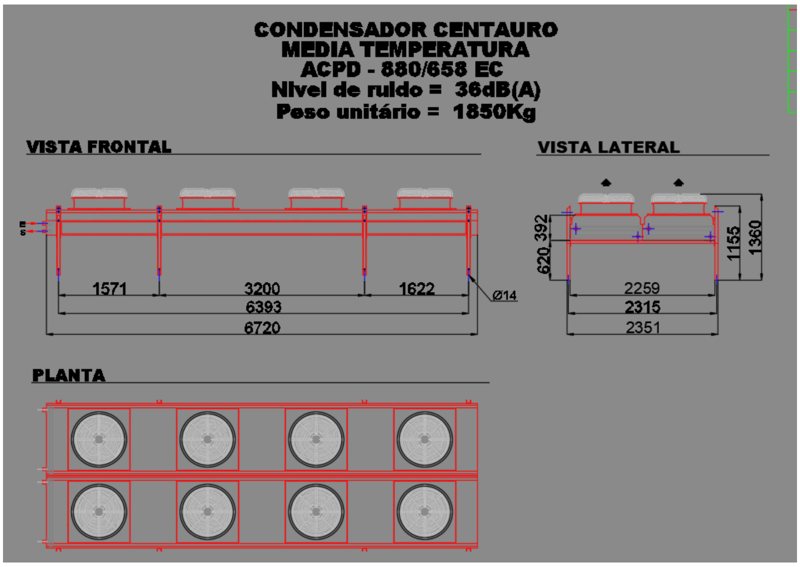
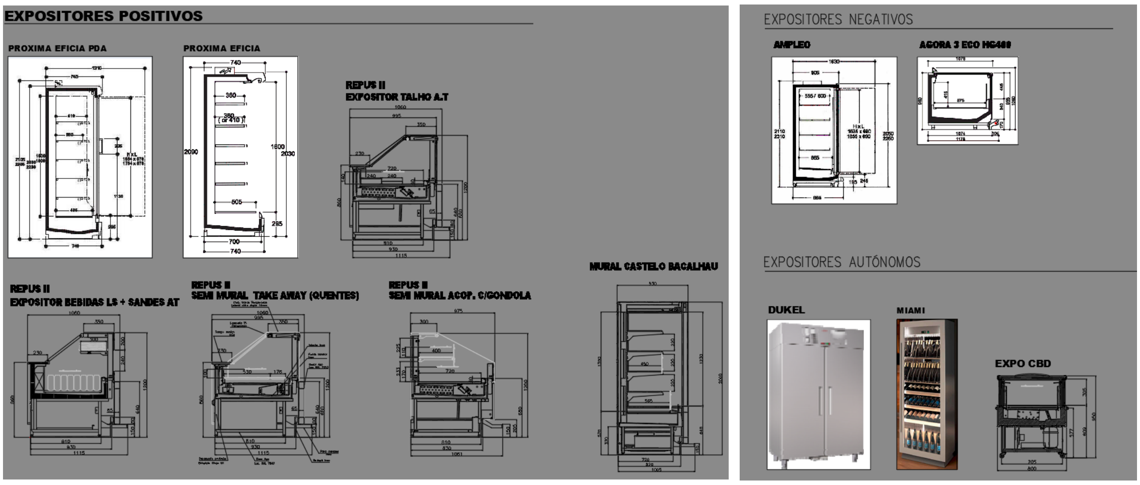


Figure 3.16: Gas cooler of the installation.

3.3.1.3 Remote Display Cabinets and Stand-Alone Units

Display cabinets and plug-in units used in this supermarket can be seen in Figure 3.17, as the sum of TDA of all equipment is equal to 149.12 m^2. For theoretical consumption, plug-ins consume 152.93 kWh/24h and the DEC of remote display cabinets consume only 188.29 kWh/24h. This consumes, summed up with the ones from the ancillary components of the cold rooms give a total DEC + plug-in units of 341.22 kWh/24h. Total values for TEWI's calculation are synthesized in Table 3.10.



(a) (b)

Figure 3.17: Display cabinets used in Supermarket C. (a) Remote display cabinets for positive temperatures (R134a cycle). (b) Remote display cabinets for negative temperatures (R744 cycle) and plug-in units.

Table 3.10: Summary of parameters to calculate theoretical DEC, TDA and total room volume of Supermarket C.

Parameters	Plug-in Units (R290)	Remote Display Cabinets (R744)	CSR (R744)	Remote Display Cabinets (R134a)	CSR (R134a)	Ice Machine + Gas Cooler	Total
Theoretical Energy Consumption [kWh/24h]	152.93	45.28	7.58	80.07	15.92	39.44	341.22
Total Room Volume [m^3]	-	-	46.98	-	147.36	-	194.33
TDA [m^2]	8.87	46.33	-	93.92	-	-	149.12
Refrigerant Charge [kg]	1.20	-	-	-	-	-	-

3.4 Energy Consumption Analysis and Discussion

After characterizing the three supermarkets, it is time to analyze their actual energy consumption, individually, to see how each facility behaves. The data available for this analysis were collected from the control and monitoring systems existing in supermarkets. For some months there were recorded reading errors and missing data, perhaps due to vibrations or measuring devices that could be damaged, so, as TEWI requires an annual energy consumption value for the calculations, to avoid the time periods that would be analyzed being different from store to store, some projections of the real consumption data were made based on the theoretical data. All electricity comes from the grid.

3.4.1 Data Analysis for Supermarket A

This supermarket has two electric meters and a thermometer for the ambient temperature, that register the measurements hour by hour in kW and in ºC, respectively. One of the electric meters measures all the electricity consumed for refrigeration activity in the supermarket and the other one measures the electricity consumed by the RCUs; their value difference, on each hour, corresponds to the electricity consumed by the plug-in units, evaporators and defrost of the cold storage rooms. Figure 3.18 expresses the variation of total energy consumption used for refrigeration by day, from April 2024 to March 2025, accounting a period of 12 months. The temperature for the month of April was unknown, so it was assumed that it was the average value between the average maximum temperature and the average minimum temperature for that month (16ºC), according to IPMA's report, which can be found in Appendix D.

The graph shows the supermarket's daily energy consumption over the course of a year, as well as the ambient temperature recorded in the vicinity of the location. Some observations can be made from this graph, such as the variation in energy consumption, represented by the solid line, where its peak is reached sometime in August and its minimum sometime in January, an expected consequence of seasonal variations (in this case it is a maximum variation of around 140 kWh). Looking at the overall picture, the fluctuations show small variations, as the energy consumption oscillates around a restricted range of values, normally from 500 kWh on colder days to 700 kWh on hot days, and it is at these points that it comes closest to theoretical energy consumption. It can also be observed that the behavior of the consumption line follows the behavior of the temperature line, with maximums and minimums, but with smaller variations, which will be analyzed

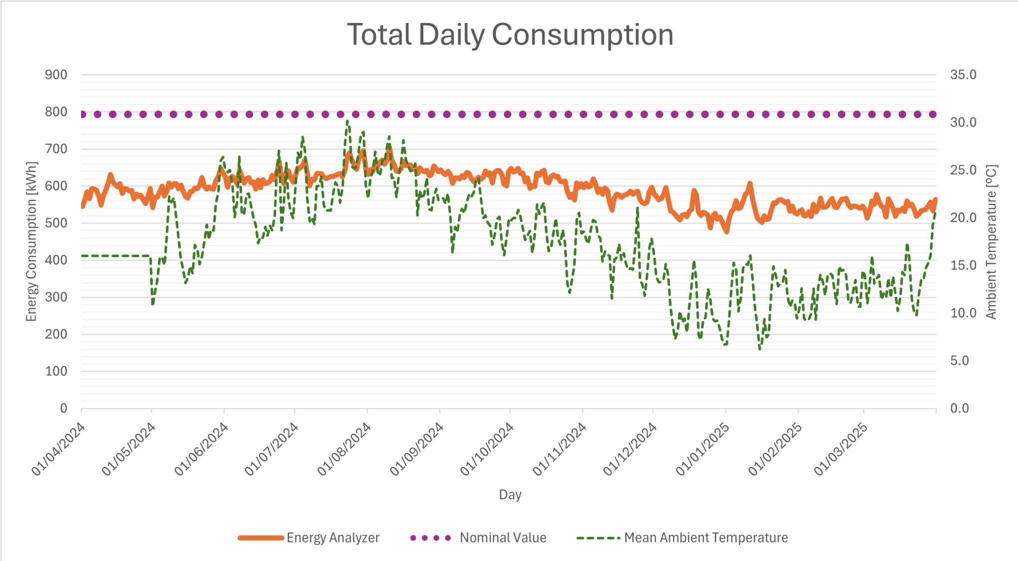


Figure 3.18: Total daily consumption of energy used for refrigeration in Supermarket A.

in more detail in Figure 3.19, below. The ambient temperature, represented by the line, presents fluctuations typical of what would be expected for the Portuguese climate.

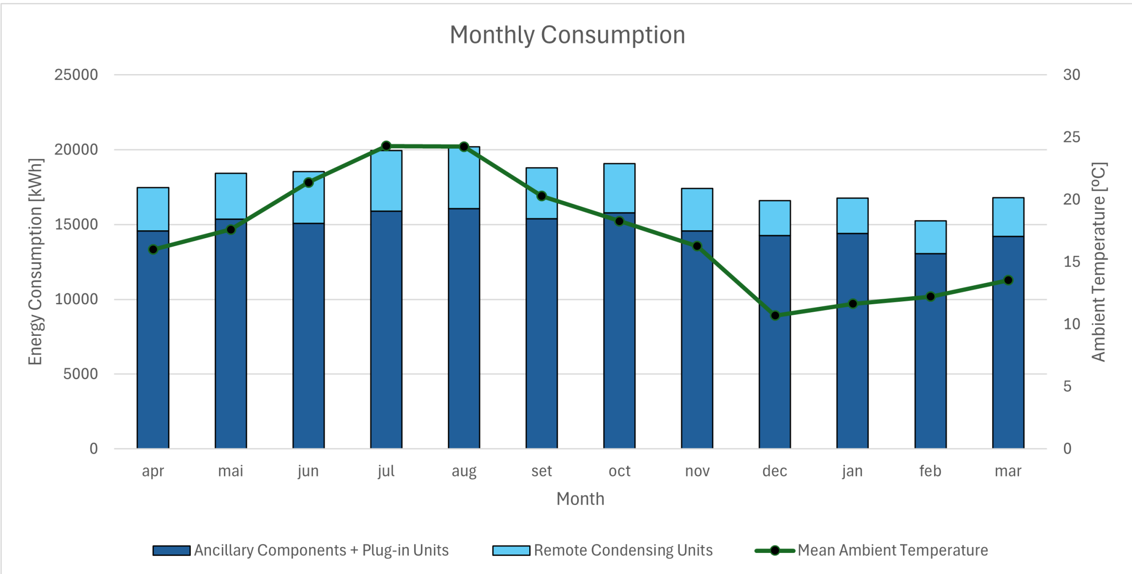


Figure 3.19: Monthly consumption of energy used for refrigeration in Supermarket A.

The graphic shows the monthly energy consumption and mean ambient temperature over a year, with energy consumption divided between *Ancillary Components + Plug-in Units* (represented by the dark blue color, on which its total energy consumption is 178654 kWh/year) and *Remote Condensing Units* (represented by the light blue color, with an annual consumption of 36675 kWh/year). It is possible to observe a correlation between energy consumption and ambient temperature. Consumption tends to increase during the warmer months, as refrigeration systems require more energy to ensure heat is released to the outside. In the colder months, energy consumption decreases slightly, reflecting the reduced need for cooling. Therefore, the relationship between energy consumption and temperature is clear, with consumption peaks coinciding with the months of highest temperature (June and July).

Despite this, energy consumption shows a relatively stable trend throughout the year. Most of the consumption comes from *Ancillary Components + Plug-in Units*, equipment known for consuming a lot of energy, especially those that use electrical heaters for defrosting, dissipating a lot of heat to the surroundings that will not be used. Another fact that can lead to this results is that these equipments often operate continuously or in long cycles to maintain optimal temperature conditions even when RCUs are not operating. Additionally, this supermarket has many more auxiliary components than RCUs, and the former may not be as efficient as the latter, as the graph shows that RCUs remain more stable, are very efficient and have low energy consumption (only two remote condensing units operating). Furthermore, it is worth keeping in mind that as there are months with fewer days than others, consumption is also affected by this.

In summary, energy consumption for this case is clearly influenced by seasonal temperature changes, with an increase in summer and a slight decrease in winter, with most of the consumption being attributed to *Ancillary Components + Plug-in Units*. The total annual energy consumption of this supermarket is 215,329.0 kWh/year.

3.4.2 Data Analysis for Supermarket B

Supermarket B has two electric meters, one of which measures all the electricity consumed by the supermarket's compressors (REC) and the other measures the electricity consumed by the auxiliary components (DEC) and plug-in units. Figure 3.20 expresses the variation in total energy consumption used for refrigeration per day, from September 2024 to March 2025, covering a period of 7 months. Data from April to August was missing, so some estimates will be made later to be possible to calculate TEWI for a whole year. It also has a thermometer that measures the temperature outside the store.

Compared to Supermarket A, this is a much larger store, with more equipment and cold rooms, but, looking at the figure below, its total consumption has significant fluctuations and is much lower for the coldest period than in the case of Supermarket A, since most of its energy is consumed by compressors, equipment that is quite sensitive to variations of outside temperature. For example, from September to the first days of December, its consumption is higher compared to Supermarket A, but after that, consumption decreases significantly, reaching only 440 kWh in January, unlike the first store where its consumption is more constant over time.

Figures 3.21 and 3.22 show the evolution of DEC and REC trough the analyzed period of time. In this case, the low variation in energy consumption for auxiliary components and plug-in units is even more noticeable than in the previous case. This happens because these components release heat into the store environment, which is always between 20ºC and 25ºC throughout the year, depending on heating needs; often, slight variations in temperature also occur due to the opening of doors by customers or the opening of doors of cold storage rooms by workers. Thus, as can be seen in the figure below, DEC has a weak direct relationship with the average external

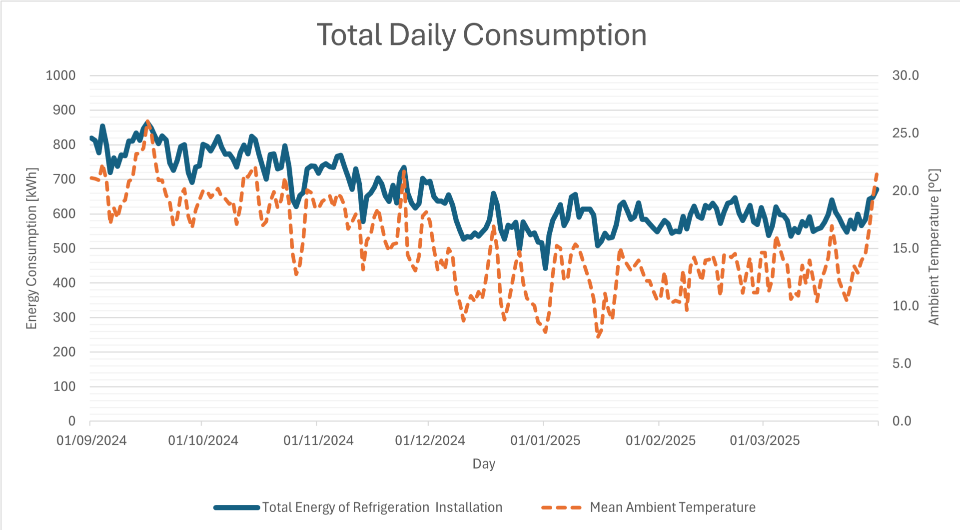


Figure 3.20: Total daily energy consumption of the refrigeration installation of Supermarket B.

temperature. On the other hand, it can be observed that the behavior of the compressors in relation to the behavior of temperature are completely interconnected, with the two lines being almost identical. This relation is what makes compressor consumption highly variable, which is why they are more efficient, and in the case of ancillary components or plug-ins the opposite happens, having a regular consumption throughout the year.

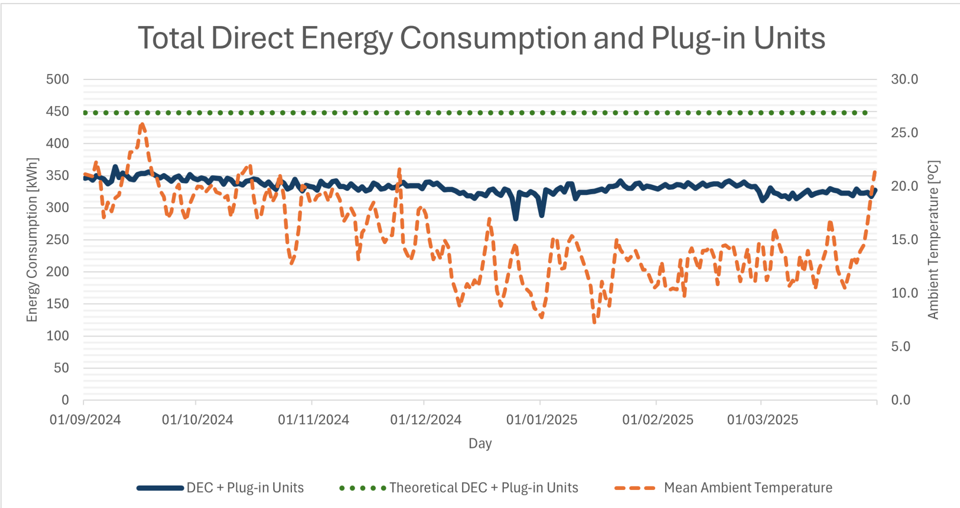


Figure 3.21: Total daily energy consumption of plug-in units and ancillary components for Supermarket B.

As mentioned previously, it can be clearly seen in Figure 3.23 that the compressors adapt to temperature needs and therefore present large variations in their consumption, which can vary between 14 MWh in September and 7 MWh in February. As for auxiliary components, as they present constant values throughout the year, their maximum variation is only 150 kWh. For example, in September energy consumption corresponds to practically 50% for each side, but when the

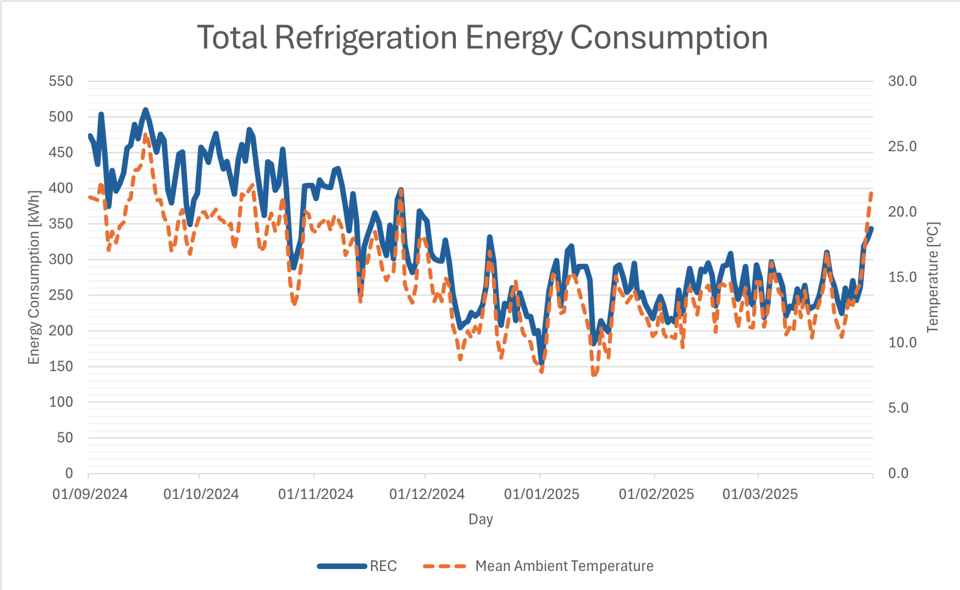


Figure 3.22: Total daily energy consumption by the compressors of Supermarket B.

winter months arrive the drop in REC is noticeable, while the variation in DEC is much smaller, thus being responsible for the majority of energy consumption in colder months.

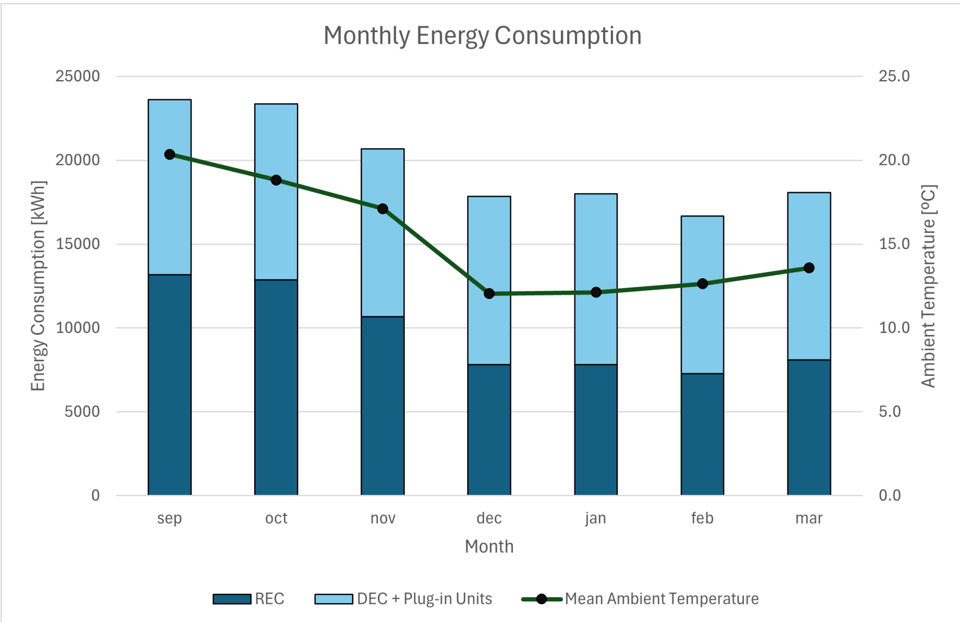


Figure 3.23: Monthly energy consumption of the refrigeration installation of Supermarket B.

As there are only 7 months of consumption data available, to estimate the real values missing for REC, *Pack Calculation Pro software* can create an annual load model for the compressors' behavior and, therefore, it was used to obtain theoretical energy consumption values of the central refrigeration system and subsequently use these values to predict the real ones, using a correction factor. Using this *software*, it was necessary to selected the option for transcritical CO_2 system with parallel compression and then select the *Bitzer* compressors chosen for this project, already mentioned previously. A standard configuration for this type of system can be seen in Figure 3.24.

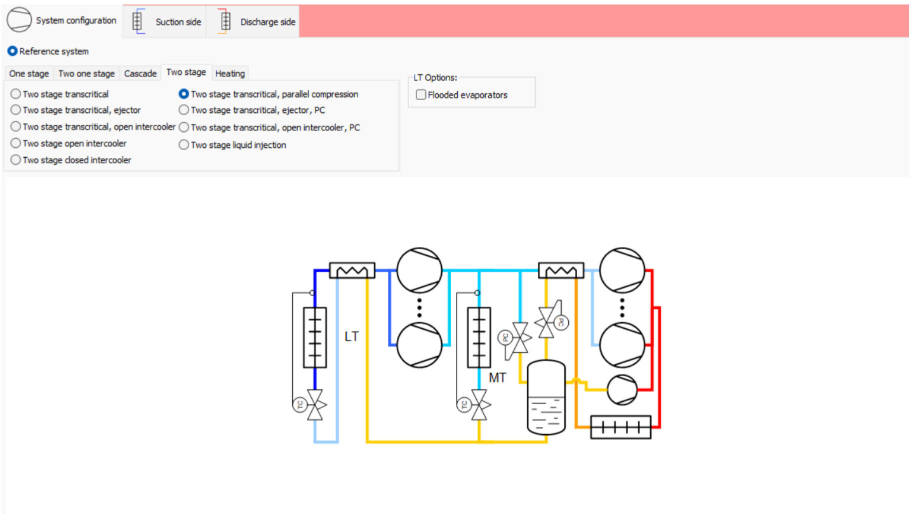


Figure 3.24: Central system configuration (from *Pack Calculation Pro*).

The compressors' selection is represented in Figure 3.25, such as the cooling capacities for both LT and MT cycles which is automatically calculated by the *software*. After this action, it is necessary to select the place that is being studied, for having a simulation closer to real climate conditions. For Porto, the set of climatic files used is IW2, like it is represented in Figure 3.26. Finally, it is possible to calculate the monthly energy consumption and the results are represented in Figure 3.27.

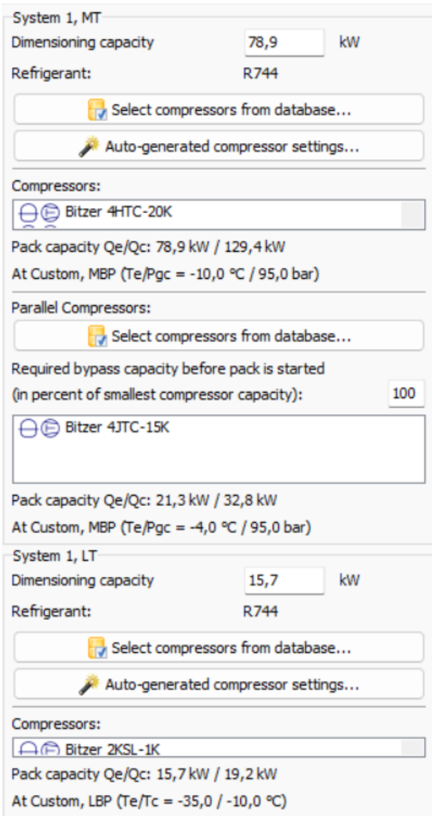


Figure 3.25: Command for selection of the compressors and cooling capacities projected.

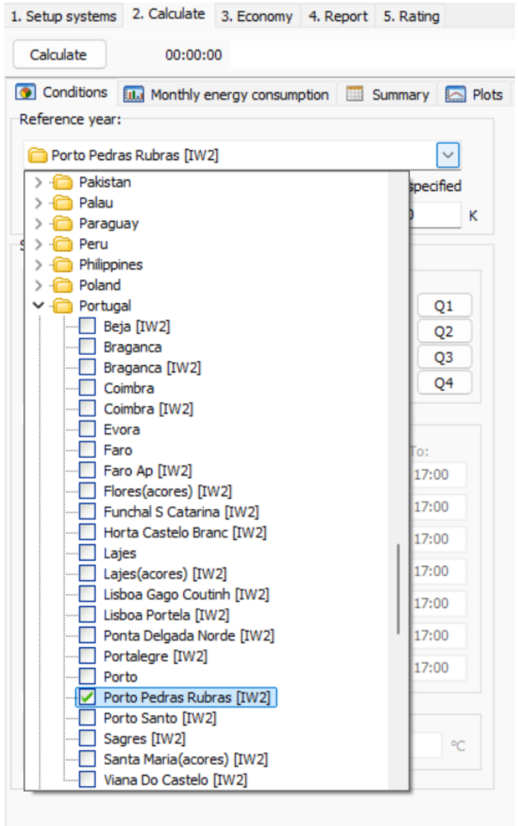


Figure 3.26: Selection of local and climate (from *Pack Calculation Pro*).

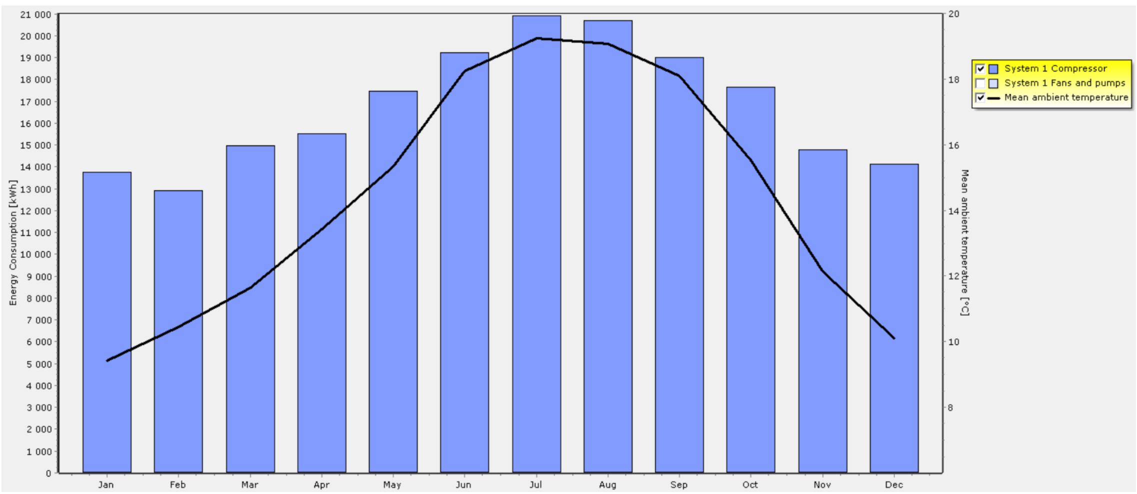


Figure 3.27: Annual load model for energy consumption of the compressors for Supermarket B (from *Pack Calculation Pro*).

With the values obtained in the simulation (theoretical REC, REC_T), first, a correction factor was calculated for each month with available real data ($\frac{REC_R}{REC_T}$); then, its average was calculated, being equal to 0.62. After that, equation 3.2 was applied to all months from April to August to estimate a real REC (REC_R). This process is expressed with more detail in Table 3.11.

$$REC_R \text{ [kWh]} = \text{Correction factor} \cdot REC_T \tag{3.2}$$

Table 3.11: Projection of REC for the months with missing data using a correction factor.

Month	REC_R [kWh]	REC_T [kWh]	Correction factor ($\frac{REC_R}{REC_T}$)	Projection for REC_R [kWh]
2024				
April	-	15,517.3	-	9,690.2
May	-	17,449.2	-	10,896.6
June	-	19,210.9	-	11,996.7
July	-	20,914.7	-	13,060.7
August	-	20,694.5	-	12,923.2
September	13,176.8	19,010.8	0.69	13,176.8
October	12,857.1	17,637.9	0.73	12,857.1
November	10,671.2	14,797.4	0.72	10,671.2
December	7,806.7	14,113.9	0.55	7,806.7
2025				
January	7,823.3	13,742.4	0.57	7,823.3
February	7,283.4	12,903.1	0.56	7,283.4
March	8,100.0	14,966.0	0.54	8,100.0
Mean correction factor	-	-	0.62	-
Energy Consumption [kWh/year]	-	-	-	126,285.8

To project the missing data on the DEC, something similar was done, but now considering the calculated daily theoretical value and then multiplying it by the number of days in each month. Correction factors were then calculated for the months with existing real data. As can be seen in Table 3.12, the mean correction factor is 0.74. Multiplying this value for the theoretical DEC for the months between April and August, the total DEC for the period studied is then 121,476.90 kWh and so, the total annual consumption is equal to 247,762.70 kWh/year.

3.4.3 Data Analysis for Supermarket C

For this store, there is again two electric meters, but this time there is one meter connected to every equipment who operates at positive temperatures and another one connected to every equipment who works with negative temperatures, so values for REC and DEC are together. Data is available for a period of 12 months, between April 2024 and March 2025. Figure 3.28 shows the daily behavior of the total energy consumption for all equipment whose operating temperature is positive, which includes the REC of the compressors for the R134a cycle, TEC of positive plug-in units and DEC of fans and defrost heaters of cold storage rooms, remote display cabinets and condenser. The same happens for the equipment who works with negative temperatures. Variation of mean ambient temperature and the theoretical value for DEC are also in the graph.

By this figure, it can be observed that positive equipment its the one who consumes more energy throughout the year, with values frequently higher than 800 kWh per day but that can

Table 3.12: Projection of DEC for the months with missing data using a correction factor.

Month	DEC_R [kWh]	DEC_T [kWh]	Correction factor	Projection for DEC_R [kWh]
2024				
April	-	13,508.8	-	9,986.22
May	-	13,959.1	-	10,319.09
June	-	13,508.8	-	9,986.22
July	-	13,959.1	-	10,319.09
August	-	13,959.1	-	10,319.09
September	10,442.3	13,508.8	0.77	10,442.3
October	10,509.0	13,959.1	0.75	10,509.0
November	10,006.8	13,508.8	0.74	10,006.8
December	10,041.4	13,959.1	0.72	10,041.4
2025				
January	10,180.6	13,959.1	0.73	10,180.6
February	9,378.3	12,608.2	0.74	9,378.3
March	9,988.8	13,959.1	0.72	9,988.8
Mean Correction Factor	-	-	0.74	-
Energy Consumption [kWh/year]	-	-	-	122,645.1

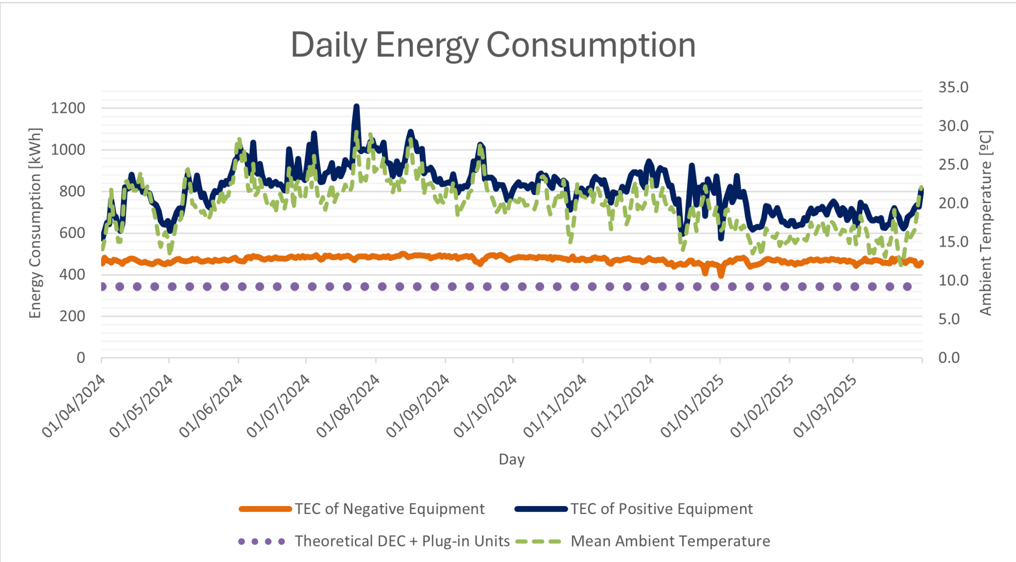


Figure 3.28: Total daily consumption for both central systems of Supermarket C.

reach to only 580 kWh/day, while negative equipment remains mostly between a stable range of 440 and 480 kWh. Furthermore, it can be seen that the positive equipment consumption varies considerably over time, following the fluctuations of ambient temperature, represented by the dashed green line. In contrast, the energy consumption of negative equipment demonstrates much more stable behavior, maintaining practically the same level of daily consumption throughout the year. This can be explained by a relationship between temperature and the need for the CO_2 system to always be stable, due to the risk of reaching high pressures; the temperature at which the refrigerant enters the heat exchanger and the temperature at which it leaves must be well controlled and kept the same throughout the year to avoid pressure increase but also to allow the cycle to function correctly (LT cycle), so that, by keeping the inlet and outlet temperatures the same throughout the year, the energy required for this cycle is almost always the same. For the MT cycle, its temperature upon entering the condenser will depend intrinsically on the ambient temperature, which is why energy consumption presents significant variations.

Analyzing Figure 3.29, it can be reinforced that, consistently, the system with R134a presents a higher monthly energy consumption than the system with R744. This pattern is maintained throughout all the months analyzed, and the difference in consumption increases in the hottest months, which suggests a greater sensitivity of the R134a system to external thermal conditions, especially between June and August, when a peak in total energy consumption is observed, coinciding with the increase in the average ambient temperature, which reaches values above 22°C, while the consumption of the R744 system remains more stable, with very small variations, since the R744 system is less affected by temperature variations. On the other hand, in the winter months, such as January and February, there tends to be a convergence of consumption for the two central systems, however, R134a system continues to consume more energy and R744 system remains stable. The annual TEC for positive equipment is 172,438.0 kWh/year and TEC for negative equipment is 295,630.0 kWh/year, which means the total energy consumption of the installation for the period considered is 468,068.0 kWh/year.

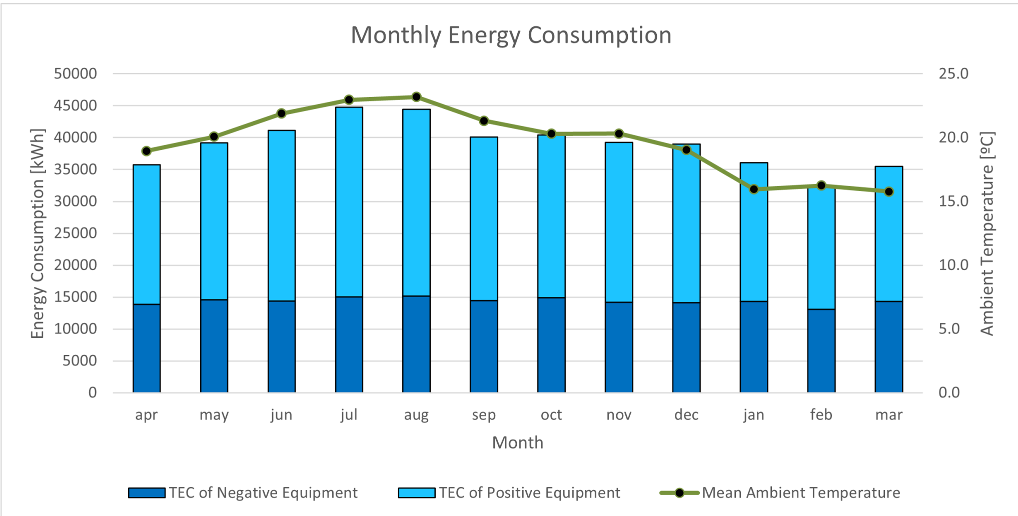


Figure 3.29: Monthly consumption for both central systems of Supermarket C.

In short, it is clear after this analysis of different solutions that centralized systems have lower fixed consumption (DEC) and higher REC consumption, but are more variable and more efficient according to temperature variations. Systems with a higher proportion of autonomous/plug-in equipment are more resistant to temperature variations and, therefore, have almost "fixed" consumption throughout the year. Comparing the two types of solutions, centralized and decentralized, in the summer, the centralized solutions consume more energy than the decentralized solution, partly due to the greater number of equipment, however, in the winter the decentralized solution ends up consuming much more energy than the centralized solutions.

The next chapter will focus on TEWI.

Chapter 4

TEWI Calculation

The period of energy consumption studied is a whole year from April 2024 to March 2025. The actual data on total energy consumption has already been discussed previously, but is recalled below for later calculations:

- Supermarket A: 215,329.0 kWh/year
- Supermarket B: 247,762.7 kWh/year
- Supermarket C: 468,068.0 kWh/year

Refrigerant charge was already determined for every case on the last chapter. GWP for refrigerants is also already known. It is also necessary to address the annual leakage rate for each supermarket, considerations on the useful life of equipment, the recovery factor of refrigerants and the indirect emission factor for the year 2024, which will be presented below.

4.1 Annual Leakage Rates

The annual leakage rate is calculated as being the quantity of refrigerant that was lost by the system during a whole year, as expressed in Equation 4.1.

$$L_{annual} = \left(\frac{\text{Quantity lost by leaks}}{\text{Number of years}} \right) \left[\frac{kg}{year} \right] \tag{4.1}$$

The amount of refrigerant lost in the year 2024 will be equal to the amount of refrigerant supplied to supermarkets in the same year to replace what is missing and reach the system's full refrigerant charge again. Therefore, after consulting the After-Sales Department, the information provided was as follows:

1. For Supermarket A were supplied 3 bottles of R290 with 370g each. There is no data about R744 or R449A;
2. For Supermarket B were supplied 2 bottles of R744, each one with 37.5 kg. There is no information for R290 of plug-in units;

3. For Supermarket C were supplied 110 kg of R134a, 45kg of R744 (3 bottles of 15kg). No information for the plug-in units.

As it can be noticed, there is a lack of data for certain systems, mostly stand-alone systems, which may not be a major problem since these equipments can only support 0.15 kg at maximum. For the RCUs, refrigerant charge varies between 1 to 10 kg, which is not a high charge too, so, according to [10], the annual leakages of this two types of equipment are very low in comparison to the ones of centralized systems, not having great influence on the calculations. However, for the data that does exist, the annual leakage rates for the year of 2024 of the supermarkets respectively by the order above, are:

- Supermarket A: $L_{annual,R290}$ = 0.37 kg/year
- Supermarket B: $L_{annual,R744}$= 37.5 $\times$ 2 = 75 kg/year
- Supermarket C: $L_{annual,R134a}$ = 110 kg/year
- Supermarket C: $L_{annual,R744}$ = 45 kg/year

The justification for the high leakage rates in the year of 2024 at Supermarket C was associated with the vibration felt by the supermarket's structure due to the intervention and works of the metrobus near the supermarket location. CO_2 leaks are also explained by the reason that on cascade systems, when the positive cycle reaches the optimum temperature, the cycle stops, which causes the temperature to increase or, on hotter days, the energy lost by R134a in the condenser will be less. In consequence, the temperature of R134a entering the heat exchanger is going to be higher than normal, therefore the temperature difference on the heat exchanger will be smaller, which means that less heat is exchanged between R744 and R134a. This forces R744 to leave the heat exchanger at a higher temperature/pressure than expected, which can increase very quickly. This sudden increase in pressure activates the safety valves that release part of the refrigerant, reducing the volume of fluid in the system; as a consequence, the internal pressure tends to drop rapidly.

4.2 TEWI Calculation Using the Model

The useful life that an equipment can have can be different from the time that the equipment actually is able to work, as supermarket owners often change their equipment before it reaches the end of its useful life because it becomes obsolete, since they look for more innovative and aesthetic equipments. Thus, based on industry experience, the time for an equipment to be replaced usually varies from 12 to 15 years. For this study, the useful life of all equipment will then be considered to be 15 years. When the equipment is replaced and its refrigerant is extracted, the recovery factor for the refrigerant will be at least 70%, often because below this value the refrigeration cycles cannot even function properly.

For the indirect emission factor (β) of the year 2024, Table 2.1 from Chapter 2 was used to establish a projection of its value. According to the equation in Figure 4.1, the projection of β for

2024 is going to be 0.141 kg CO_2e/kWh and it will be assumed that for the period of 15 years studied this factor will be constant (TEWI is a metric accumulated over the useful life).

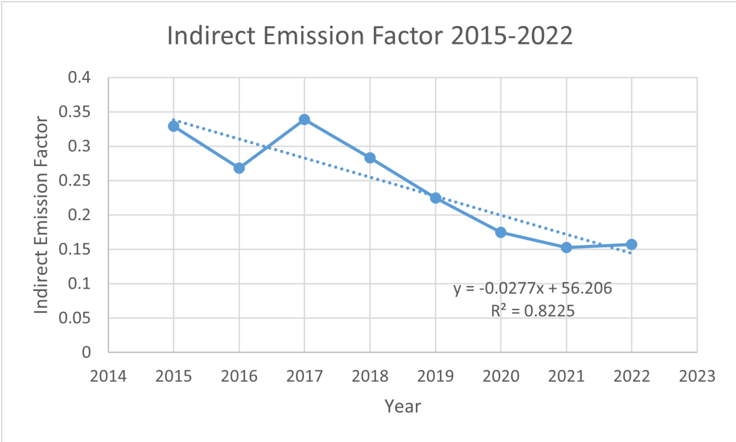


Figure 4.1: Projection for β for the year of 2024.

In this section, the Total Equivalent Warming Impact (TEWI) of Supermarket A will be calculated and then explained in detail, using a spreadsheet tool that was developed to facilitate this assessment, allowing the estimation of direct and indirect emissions of CO_2 equivalent, associated with the refrigeration systems. This tool includes all parameters such as leak rates, energy consumption and equipment lifespan as inputs, making it easily usable for all types of refrigeration systems used currently in supermarkets.

While the detailed analysis focuses on Supermarket A, the same calculations were done for the remaining supermarkets studied. These results are compiled and presented in Appendix E.

Remembering the equation to calculate TEWI, Equation 4.2 shows that the two first terms are assigned for the direct emissions and the last term is related to energy consumption.

$$\text{TEWI}[kgCO_2e] = GWP \cdot L_{annual} \cdot n + GWP \cdot m \cdot (1-\alpha) + E_{annual} \cdot \beta \cdot n \tag{4.2}$$

As can be seen, the calculation of the last term is not related to the properties of the refrigerant used (GWP, annual leakage and refrigerant charge), therefore, it can be said that this term is independent of the working fluid and so, this term can be only calculated once, using the total value of the installation's energy consumption.

Figure 4.2 describes part of the calculation tool done in Excel to obtain TEWI not only for Supermarket A, but for any system solution a supermarket can have. Analyzing the calculation tool in more detail, first there are the inputs of system operating lifetime, recovery factor and indirect emission factor which, as they were considered the same for any case, present fixed values. Now, in the case of parameters that depend on the refrigeration solution assigned to each supermarket, for Supermarket A there are no centralized systems, only plug-in and remote condensing units, so the spaces corresponding to these equipments were filled with the values obtained in this chapter and in the previous one. There are two sections in the case of plug-in units, the one for equipment that works with R290, and one for the ice machine, which works with R449A (GWP=1397). Energy consumption is separated into the RCUs and Plug-in sections, but could equally be grouped into just one of the sections for the reason already mentioned above.

TEWI CALCULATION					
System Operating Lifetime (n)	15				
Indirect Emission Factor (β)	0.141	[kg CO2e/kWh]			
Recovery Factor (α)	0.70				
Centralized System	No				
Negative Refrigeration Cycle			Positive Refrigeration Cycle		
Refrigerant	-		Refrigerant	-	
GWP	-		GWP	-	
Annual Leakage Rate (Lannual)	-	[kg/year]	Annual Leakage Rate (Lannual)	-	[kg/year]
Refrigerant Charge (m)	-	[kg]	Refrigerant Charge (m)	-	[kg]
Annual Energy Consumption (Eannual)	-	[kWh/year]	Annual Energy Consumption (Eannual)	-	[kWh/year]
Plug-in Units	Yes				
Refrigerant	R290		Refrigerant	R449A	
GWP	3		GWP	1397	
Annual Leakage Rate (Lannual)	0.37	[kg/year]	Annual Leakage Rate (Lannual)	-	[kg/year]
Refrigerant Charge (m)	6.01	[kg]	Refrigerant Charge (m)	0.15	[kg]
Annual Energy Consumption (Eannual)	178654	[kWh/year]	Annual Energy Consumption (Eannual)	-	[kWh/year]
Remote Condensing Units	Yes				
Refrigerant	R744				
GWP	1				
Annual Leakage Rate (Lannual)	-	[kg/year]			
Refrigerant Charge (m)	24.5	[kg]			
Annual Energy Consumption (Eannual)	36675	[kWh/year]			

Figure 4.2: Inputs of the spreadsheet tool.

Moving on to the results of TEWI calculation for the Supermarket A installation, these are summarized in Figure 4.3. The figure shows the TEWI value of each refrigeration subsystem, and also the contribution of each one in terms of direct and indirect emissions. The sum of the TEWI for these two subsystems makes up the TEWI of the facility, which assumes that 455.5 tons of CO_2 equivalent will be emitted over the lifetime of the facility. As shown, plug-in units are responsible for the largest share of the installation's CO_2e emissions, amounting to a total TEWI of approximately 377.9 tonnes of CO_2e, with the vast majority resulting from electricity consumption. Remote condensing units contribute a further 77.6 tonnes of CO_2e, again predominantly through indirect emissions.

Centralized System (Negative)					
Indirect Emissions	-	[kg CO2e]			
Direct Emissions	-	[kg CO2e]			
TEWI	-	[kg CO2e]			
Centralized System (Positive)					
Indirect Emissions	-	[kg CO2e]			
Direct Emissions	-	[kg CO2e]			
TEWI	-	[kg CO2e]			
			TEWI of installation	455513.1	[kg CO2e]
				455.5	[ton CO2e]
Plug-in Units					
Indirect Emissions	377853.21	[kg CO2e]			
Direct Emissions	84.92	[kg CO2e]			
TEWI	377938.13	[kg CO2e]			
Remote Condensing Units					
Indirect Emissions	77567.63	[kg CO2e]			
Direct Emissions	7.35	[kg CO2e]			
TEWI	77574.98	[kg CO2e]			

Figure 4.3: Output of the spreadsheet tool.

4.2.1 Discussion of Results

After repeating this process for the other two supermarkets, direct and indirect emissions as well as the TEWI for each facility are summarized in Table 4.1 and illustrated in Figure 4.4. From this table it is possible to see the discrepancy in TEWI between the cascade system and the other systems, suggesting that Supermarket C refrigeration system emits more CO_2e to the atmosphere, either through higher energy consumption, higher necessity of refrigerant charge, higher leak rates, or a combination of all these factors. The fact that the GWP of R134a is 1430 compared to the GWP of R744 which is 1 or R290, GWP=3, cause direct emissions to skyrocket and exceed indirect emissions (but are still higher than those of the other solutions) with the help of the main disadvantage of centralized systems which is the length of refrigerant pipes associated with a large refrigerant charge (already mentioned in Chapter 2); also to support this value of direct emissions, there is the issue of the high number of leaks due to works in 2024 close to the area of the supermarket, reminding that, emitting 1 kg of R134a causes a damage equivalent to emitting 1430 kg of CO_2. A study realized about a conventional refrigeration system using a HFC against a transcritical system, presents for the first case a higher TEWI due to direct emissions, which were almost inexistent for the second case [29].

Table 4.1: Direct, indirect emissions and TEWI for each facility studied.

	Supermarket A	Supermarket B	Supermarket C
Direct Emissions [kg CO_2e]	92.3	1,173.6	248,8927.1
Indirect Emissions [kg CO_2e]	455,420.8	524,018.1	989,963.8
TEWI [t CO_2e]	455.5	525.1	3,478.9
Direct Emissions [%]	0.02%	0.22%	71.54%
Indirect Emissions [%]	99.98%	99.78%	28.46%

The dominance of indirect emissions over direct emissions is clearly noticeable for the first two cases. In Supermarket A and Supermarket B, emissions are mainly influenced by indirect emissions (more than 99.9% and 99.7%), that is, emissions from the consumption of electricity. Direct emissions are residual in these cases, which indicates good leak control, use of refrigerants with low GWP and/or small refrigerant charge, as mentioned before.

It was decided to study a cascade system working with R134a because it is one of the most widely used refrigerants in the world, and, although refrigeration systems are no longer manufactured, as those that exist continue to operate and can be retrofitted. To reduce CO_2 equivalent emissions, retrofitting HFC systems with low GWP refrigerants such as HFO can be a good solution, since although R134a can still be used in some situations. R134a should be replaced as soon as possible due to this high emissions but also due to F-Gas Regulation because, according to Figure 2.17, by 2032 it will be no longer possible to introduce virgin refrigerants with GWP > 750 in systems. This fact is proven when analyzing its TEWI value and, especially, its direct emissions, which are around 72% of total emissions.

Figure 4.4: TEWI of the supermarkets studied.

In the case of the transcritical CO_2 solution, this presents an advantage over the Supermarket A solution because it presents a greater number of cold rooms and display units with cold requirements and yet both energy consumption and TEWI results have very similar values, but this will be studied in more detail below to see which could be the most efficient solution. It was previously discussed in the last chapter that centralized system installations were more energy efficient than stand-alone ones due to the adaptability of the compressors in relation to temperature.

When establishing some TEWI metrics to have a more detailed view of the emissions linked to the amount of cold rooms/display cabinets needed to cool, the TEWI/Vol and TEWI/TDA metrics were calculated for each supermarket and shown in Table 4.2. Both metrics are best illustrated in Figures 4.5 and 4.6. As can be seen in the analysis, both in relation to the total volume of cold storage rooms and in relation to the TDA of the display cabinets, the value of both metrics are lower in the case of the R744 transcritical system, and it can be concluded that, to meet the same needs per m^3 of cold storage room and per m^2 of exhibited area of display cabinets, the transcritical system under study does so with lower TEWI emissions than the other solutions. Then comes Supermarket A with results not far from Supermarket B and by last Supermarket C, as would be expected.

Table 4.2: TEWI per m^3 of cold storage rooms and per m^2 of exhibited area of display cabinets.

	Supermarket A	Supermarket B	Supermarket C
TEWI/Vol [t CO_2e/m^3]	2.1	1.3	17.9
TEWI/TDA [t CO_2e/m^2]	4.2	3.3	23.3

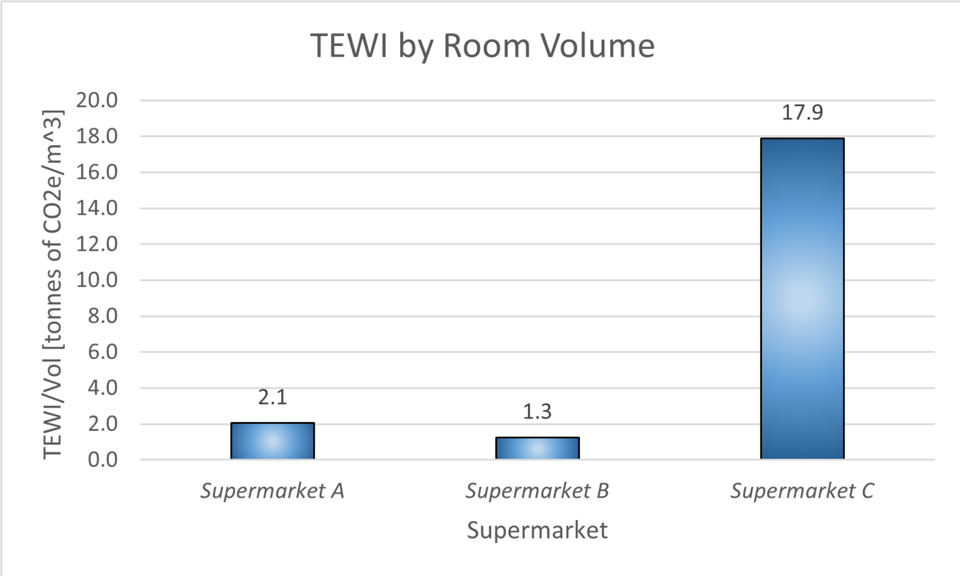


Figure 4.5: TEWI per room volume for each supermarket.

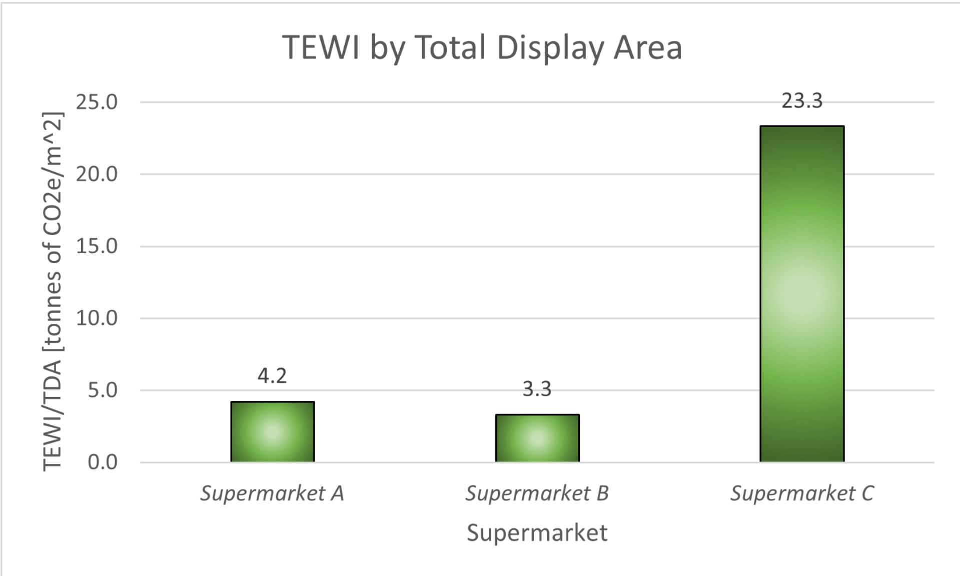


Figure 4.6: TEWI per TDA for each supermarket.

Some improvement solutions to decrease TEWI could be done for Supermarket C in terms of leak control or even retrofitting the installation by replacing R134a with lower GWP refrigerants. For the two supermarkets with residual direct emissions, energy efficiency measures like having higher COPs, thermal load optimization or better consumption control would be more useful to minimize TEWI.

As a side note, it is important to point out that the TEWI results are still missing some data on direct emissions due to the lack of data on annual leaks and, for Supermarket B, the projection made for energy consumption from April to August may also have some influence on the results, as it is an estimated value.

4.3 CapEx and OpEx

CapEx means Capital Expenditure and refers to the initial investment a company has to do to build, acquire or upgrade assets to produce products or provide services [30]. To perform a CapEx estimate on refrigeration projects, the first step is to identify all components required for implementing a physical refrigeration solution in a supermarket. This includes:

- Refrigerated production equipment: Can be remote condensing units, refrigeration plants and gas coolers, including all necessary accessories, refrigerant charge and lubricant, for the perfect functioning of the equipment/installation;
- Ice machine;
- Evaporators;
- Ducts, Duct supports and insulation: In this parameter are considered the prices for copper piping, PVC piping, elastomer foam as insulation and other components such as nuts, washers, bushings, bolts, etc.;
- Mechanical installation: Refrigerant leak detectors/indicators in all cold rooms, safety and shut-off valves, non-return valves and other security components and air curtains in the frozen chambers, only if necessary;
- Electrical installation: Related costs to the general electrical panel and partial panels, electrical wiring, electrical wiring support and lightning of cold storage rooms for the entire supermarket;
- Control and monitoring system: Set of electronic controllers;
- Miscellaneous: This section includes expenses related to the rental of cranes, forklifts and other means necessary for the perfect execution of the work, labor for the execution of the entire refrigeration installation, including installation adjustments, assembly of display cabinets in the store and the assembly of the piping networks. Also the costs of studying and developing the project before construction, reserve fluids, construction monitoring and technical assistance, in addition to a maintenance contract valid during the warranty period.

The number of display cabinets, evaporators, lengths of piping, etc., will always depend on the size of the store and the layout of the equipment, so after identifying the components and quantities required for each supermarket, the next step is to determine the unit costs of each item. These costs can be obtained through suppliers, catalogs, quotations or market research, as for materials such as copper. This will allow for the calculation of the total cost of the refrigeration infrastructure required for each type of supermarket.

The analysis must include the maintenance and durability costs of the system in addition to the initial implementation cost. While CapEx focuses on the initial investment of the system, it is important to consider, over its 15-year lifespan, the impact of component failure and replacement, such as compressors and other parts of the refrigeration system. These expenses that accompany the entire useful life of the supermarket are called OpEx (Operational Expenditure) [31], and for this work their values will be considered as a percentage of CapEx.

Simply put, the assessment that will be made of a supermarket's total investment involves finding out the initial costs of each area of refrigeration system equipment, calculating the total cost by type of solution, taking into account maintenance costs and projecting the expenses over its operating period (15 years) to identify which can be the most economical refrigeration solution.

4.3.1 Decentralized Solution

The budget for four supermarkets with plug-in units and RCUs, constructed or fully renovated in 2025, was randomly selected and analyzed by separating investment sections and then compiled as shown in Table 4.3. Of course, these budgets are conditioned by the dimensions of each store, so the prices of pipes, evaporators or display cases can vary greatly. As a note, *SR* stands for *Supermarket with Remote condensing units*.

Table 4.3: CapEx for decentralized solutions for the year of 2025.

	SR1	SR2	SR3	SR4
Refrigerated production equipment	56,904.13 €	26,458.00 €	51,652.00 €	27,370.00 €
Ice machine	12,169.00 €	9,749.00 €	11,045.00 €	10,088.00 €
Evaporators	17,892.97 €	8,441.00 €	13,524.00 €	8,734.00 €
Piping, piping supports and insulation	20,611.41 €	11,316.00 €	14,376.00 €	13,974.00 €
Mechanical installation	11,054.21 €	6,617.00 €	7,995.00 €	6,669.00 €
Electrical installation	31,624.07 €	21,463.00 €	28,887.00 €	22,210.00 €
Control system	13,716.39 €	7,511.00 €	8,290.00 €	7,705.00 €
Miscellaneous	94,437.43 €	71,136.00 €	79,779.00 €	77,523.00 €
Display cabinets	351,507.28 €	242,773.59 €	243,144.29 €	287,404.03 €
CapEx	258,409.62 €	162,691.00 €	215,548.00 €	174,273.00 €

This means that if a supermarket like Supermarket A were to be built in 2025, its average initial investment would cost 202,730.40 €. For this type of cooling solutions, OpEx has been considered as typically 5% of the CapEx value, so if we consider a period of 15 years, the total value of expenses for a decentralized solution could be around 352,730.40 €.

4.3.2 Centralized Solution: CO_2 Transcritical System

Looking at Table 4.4, at first glance, it is really noticeable that the costs of refrigerated production equipment are much higher than in the previous example; this is obviously justified by the fact that the price for a central plant with multiple compressors and a gas cooler are accounted for, versus the remote condensing units of the decentralized solution. Even all other parameters tend to have higher costs due to the dimensions of this type of store which are larger and can accommodate more equipment. *ST* stands for *Supermarket with Transcritical* system.

Table 4.4: CapEx for centralized solutions using a CO_2 transcritical system for the year of 2025.

	ST1	ST2	ST3	ST4
Refrigerated production equipment	205,034.00 €	118,605.00 €	151,309.00 €	155,731.00 €
Ice machine	28,414.00 €	14,129.00 €	15,432.00 €	19,187.00 €
Evaporators	52,715.00 €	14,569.00 €	26,049.00 €	18,233.00 €
Piping, piping supports and insulation	57,123.00 €	42,054.00 €	31,339.00 €	37,382.00 €
Mechanical installation	35,256.00 €	18,497.00 €	24,100.00 €	20,770.00 €
Electrical installation	89,550.00 €	64,896.00 €	63,896.00 €	45,197.00 €
Control system	24,553.00 €	17,727.00 €	17,085.00 €	17,068.00 €
Miscellaneous	141,787.00 €	135,867.00 €	133,210.00 €	133,993.00 €
Display cabinets	450,273.40 €	326,193.42 €	251,144.83 €	331,744.26 €
CapEx	1,084,705.40 €	752,537.42 €	713,564.83 €	779,305.26 €

The average CapEx to build a supermarket like Supermarket B in 2025 would cost around 832,528.23 €. Considering for this case an OpEx equal to 1.74% of the total CapEx value, for the established period of 15 years the total expenses will be 1,050,028.23 €.

4.3.3 Centralized Solution: Cascade System

Centralized solutions using R744 and R134a cascade systems were discontinued by the company since 2019 due to new F-Gas Regulations, however, those that have not yet reached their end of life continue to operate with this system. For this task, four budgets for supermarkets built in 2015 were used (Supermarket C was implemented a year later). Table 4.5 contains these budgets, with *SC* meaning *Supermarket with Cascade* system.

Table 4.5: CapEx for centralized solutions using a R744 and R134a cascade system.

	SC1	SC2	SC3	SC4
Refrigerated production equipment	69,319.58 €	66,924.96 €	88,755.80 €	67,991.10 €
Ice machine	11,384.60 €	11,384.60 €	12,678.60 €	12,678.19 €
Evaporators	6,054.04 €	4,245.58 €	6,140.33 €	5,302.17 €
Piping, piping supports and insulation	61,647.21 €	30,036.90 €	42,403.63 €	34,324.85 €
Mechanical installation	43,236.85 €	42,360.38 €	51,939.79 €	54,364.93 €
Electrical installation	27,198.40 €	20,211.57 €	41,980.30 €	40,532.67 €
Control system	25,891.75 €	24,414.18 €	21,215.37 €	28,868.93 €
Heat recovery system	2,550.12 €	2,550.12 €	2,550.12 €	5,726.00 €
Labor	40,861.97 €	42,030.45 €	47,279.61 €	52,163.83 €
Display cabinets	228,560.16 €	216,156.63 €	221,643.81 €	201,311.79 €
CapEx	516,704.68 €	460,315.37 €	536,587.36 €	503,264.46 €

If a supermarket with the refrigeration infrastructure like Supermarket C was built in 2015, its average initial investment would be about 504,217.97 €. Considering now that it was wanted to know what the price would be if this facility were built in 2025, the Industrial Producer Price Index (IPPI) for industry in Portugal was considered and applied to the original 2015 price. The IPPI reflects price changes in production goods for the entire Portuguese industry, such as industrial equipment/components and materials used in the manufacture of refrigeration systems [32]. Data from INE (*Instituto Nacional de Estatística*) was only available for the year of 2024 but, it shows that, in relation to 2015, the total variation on the prices evolution was of -3.3% [33]. Accounting this, the initial investment in 2024 would be about 487,578.78 €, and, considering the OpEx being 3.49% of the total CapEx value, the total cost of this installation would be 742,578.78 €. It is important to highlight that this rate considers all industrial production of goods that occurs in Portugal, and is not specific only to the materials/components used in refrigeration, and is therefore just an assumption.

The cascade system is the one with higher OpEx. This can be justified by the fact that at low ambient temperatures, R744 systems outperform traditional HFC systems. They may be less effective at higher temperatures (in warmer climates) and may be necessary to use more complex configurations such as ejectors and parallel compression, but, despite the climate zone, the investment in transcritical systems has a quicker payback due to lower operating costs [9].

4.3.4 Final Discussion

As mentioned in some literature, plug-in units are known for having lower initial cost but are less efficient than other commercial refrigeration systems [10], which still can be very attractive for investors in a first approach. Actually, and taking into account that the CO_2 transcritical system presents the highest CapEx, when analyzing the TEWI, it was concluded that, despite the difference in refrigeration systems, the volume of cold rooms and the TDA of the display cabinets between Supermarket A and Supermarket B, being higher in all cases for the latter, the differences in energy consumption and TEWI were quite close, even with the CO_2 transcritical system being more efficient when establishing TEWI metrics.

In fact, when looking at the CapEx of the three solutions, the decentralized solution has a value far removed from the two centralized solutions, which are more similar, as they require larger infrastructure, including more compressor units and piping systems. Even so, its maintenance costs, despite remaining the lowest of all (with the operating costs of the cascade system being the highest), are the costs that represent a larger share of CapEx.

The high initial investment for supermarkets like Supermarket B is justified with the fact that these types of systems must have valves/compressors and other devices specially developed to withstand the high pressures of CO_2 [34]. For example, when retrofitting a supermarket, the objective is to maintain as many components of the old installation as possible and replace the old fluid with a new one that has a lower GWP to meet new regulations; CO_2 is normally never a choice for replacement fluid in a retrofit because using this fluid for a retrofit would require changing almost the entire refrigeration installation to new components capable of withstanding the special characteristics of this fluid, incurring in higher investment [11].

To finally conclude, this study suggests that R744 transcritical refrigeration systems are the best choice from an environmental point of view, but the most expensive in terms of initial investment. Looking at the long-term investment, the R744 transcritical solution and the cascade system proved to be more expensive but very different in terms of emissions. The cascade system shows to be the worst from an environmental point of view, with exorbitant direct emissions due to its GWP. Plug-ins are not the most efficient but they are the cheapest and obviously continue to be very attractive to investors; Therefore, plug-in supermarkets are a desirable solution in smaller supermarkets since it is not worth investing in a central plant, but they should never be a choice for a large supermarket because energy consumption would be too high.

Chapter 5

Conclusions

5.1 Conclusion

The objective of this dissertation was to evaluate how various supermarket refrigeration systems affect the environment by its CO_2 equivalent emissions, as determined by the Total Equivalent Warming Impact (TEWI). Three supermarkets, which operate with different refrigeration technologies, were the subject of the study. These systems included a decentralized system with plug-in units and remote condensing units as well as a centralized transcritical CO_2 system and a cascade systems.

A detailed study of each supermarket floor plans was carried out on the identification of display cabinets and cold room evaporators, calculation of refrigerant charge, TDA, etc. The analysis also took into account the actual energy consumed by the refrigeration equipment of each installation, separating it in REC, DEC and TEC when it was possible to analyze it that way.

The study of direct and indirect emissions associated with different refrigeration systems indicated that the centralized system with transcritical CO_2 is the most efficient one, with a lower TEWI/Vol and TEWI/TDA compared to the decentralized system and significantly lower in comparison to the cascade system. On the other hand, the brief economic analysis that took into account the CapEx and OpEx of the supermarkets, revealed that, over a 15-year lifespan, the CO_2 transcritical system requires the highest initial investment. Besides this, it can be concluded that while decentralized systems are cheaper to install, they are less energy-efficient.

To promote global sustainability and achieve carbon reduction objectives like NetZero, it is recommended that supermarkets implement more energy-efficient equipments and low GWP refrigerants. Refrigerants with high global warming potential, like R134a, should be gradually replaced with lower GWP alternatives, like R744 or HFOs. The most sustainable solution for the future of commercial refrigeration has proven to be the transcritical CO_2 system, with the lowest TEWI/Vol and TEWI/TDA, even though the initial investment is higher.

Regarding the methodology adopted, this dissertation provided an excellent opportunity for collaboration with engineers and professors in the refrigeration field, enriching my knowledge on several topics, such as refrigerants, refrigeration cycles, current refrigeration solutions, operation of plug-in units, operation of refrigeration plants, etc. The work was also a valuable experience in the context of the world of work, where I had the opportunity to apply the engineering theories I learned to a practical case, developing new skills and boosting my growth as a mechanical engineer.

5.2 Future work

As future work there are some proposals:

- More supermarkets with the studied refrigeration systems could be analyzed to get to know in more detail its performance, compare their energy consumptions and verify if direct emissions follow a certain behavior depending on the operating system.
- Try to discover the total cooling capacity of the refrigeration installation and establish a TEWI metric based on that, as for the long-term investment.
- Analyze other refrigeration systems used nowadays, such as a R744 and R717 (ammonia) cascade system, which are two natural refrigerants.

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Appendix A

Supermarket Areas Studied

This appendix contains the areas of interest (cold storage rooms and display cabinets) for the stores studied.

A.1 Supermarket A Store Layout

A.2 Supermarket B Store Layout

A.3 Supermarket C Store Layout

Figure A.1: Supermarket A area of interest.

Figure A.2: Supermarket B area of interest.

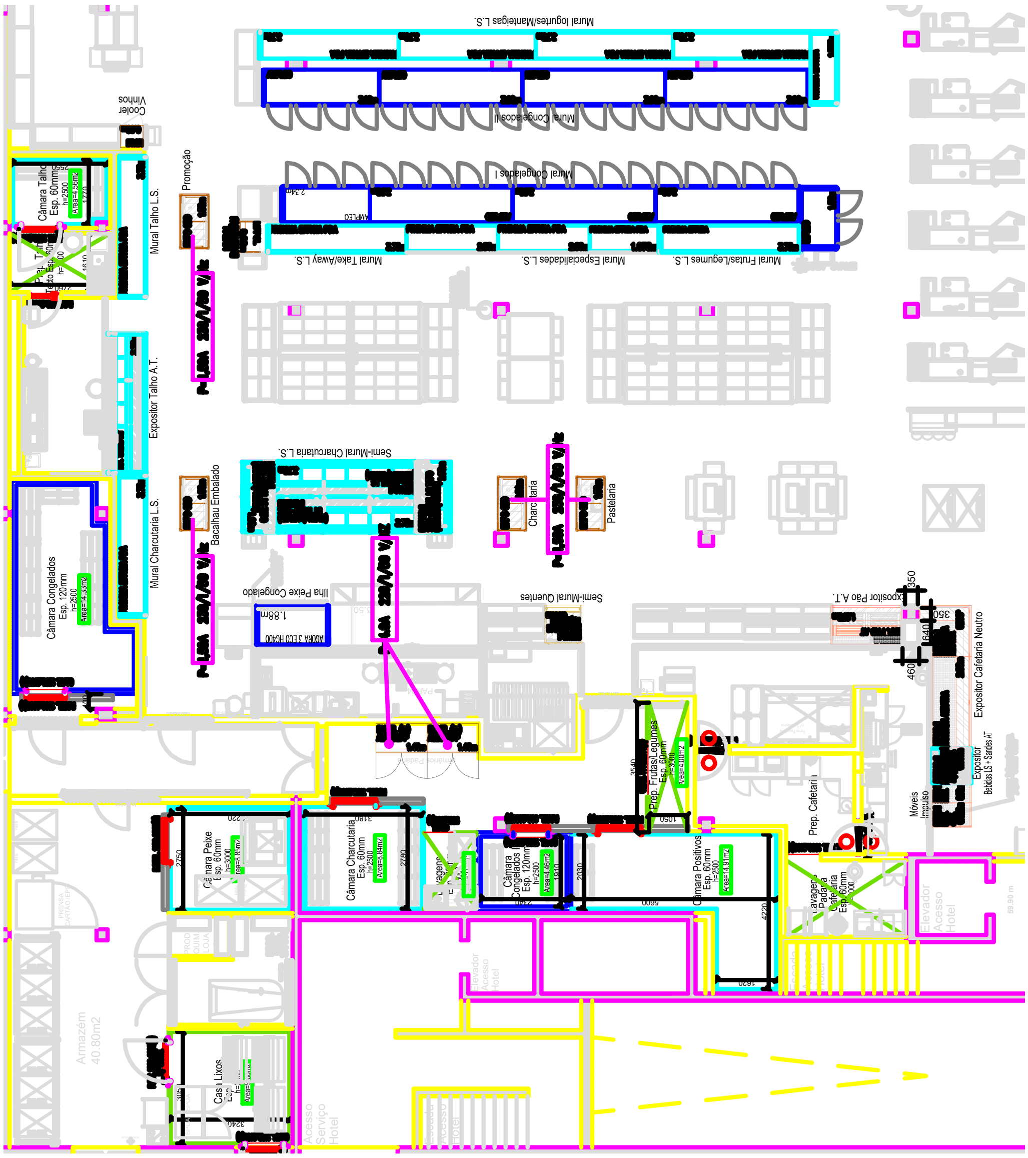

Figure A.3: Supermarket C area of interest.

Appendix B

Tutorial using *Panasonic PRO Club software*

Section where it is explained how to obtain the refrigerant charge for a installation using RCUs with *Panasonic PRO Club* software.

1. The first step to get to know the refrigerant charge for the circuit is to insert some of the data from Table 3.1, more precisely room temperature and relative humidity. Figure B.1 represents the example for the frozen chamber. Then, establish 32ºC as ambient temperature and select the RCU used in the project, from Table 3.3.

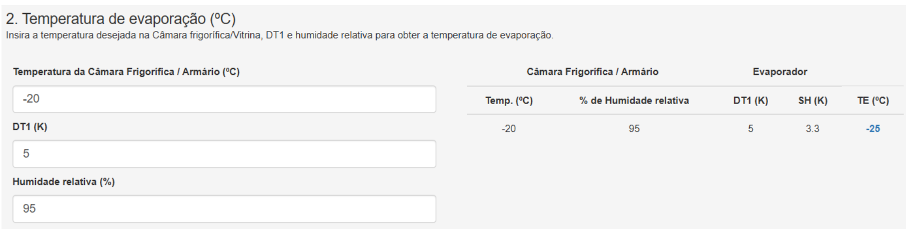

Figure B.1: First step on to calculate refrigerant charge.

2. The next step is to quantify the number of storage rooms, length of the principal pipe, length of derivation pipes and cooling capacity; for this study it was considered an efficiency of about 75%. The project plan is in 1/100 scale, so the pipe length measurements were measured directly from the printed plan and then the conversions were made.

Data to insert for frozen chamber circuit:

- Description: CC01
- Type: Cold Storage Room
- Principal pipe: 15 m
- Derivation pipes: 0 m
- Cooling capacity: 8 kW

The result obtained for the present example is going to be something like Figure B.2, that already presents the scheme of the circuit and the RCU selected, as well as the indication of which filters, valves and pipe diameters are more suitable for this installation.

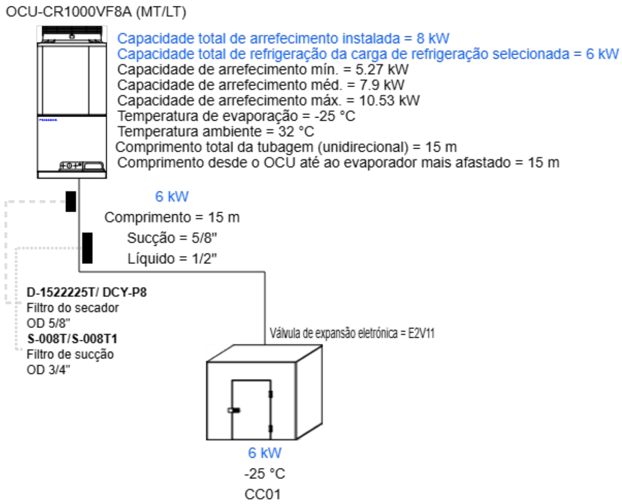

Figure B.2: Piping scheme for frozen storage room.

3. The last step before getting to now the charge of refrigerant is to indicate the internal volume of the evaporators. After this, the *software* gives a technical sheet indicating the recommended dimensions of piping, refrigerant charge (recommended and maximum) and if it is necessary to add some lubricant to the circuit.

For CC01, the internal volume of the evaporator is 19.5 dm^3, so, after introducing this value, the recommended refrigerant charge given is 12.2 kg.

Now, doing the same process for the chilled chambers circuit, firstly the values considered were:

- Room temperature = 1ºC (mean value of the three evaporators)
- DT1 = 7, being DT1 the temperature difference between the evaporator and the rooms temperatures
- Relative Humidity = 80% (equal for all)

Mean values were used because when trying to also use extreme values, the charge of refrigerant was nearly the same. After choosing the RCU, it is asked to insert the length of piping for the three cold storage rooms, like it is expressed in Table B.1.

The result given for the circuit to be installed is presented in Figure B.3.

Finally, by inserting the internal volume of each evaporator (Figure B.4), the recommended refrigerant charge given is 12.3 kg.

Table B.1: Length of piping for each cold room.

Description	Type	Principal pipe	Derivation pipes	Cooling capacity
CR01	Cold Room	9 m	3 m	6.3 kW
CR02	Cold Room	9 m	11 m	3.5 kW
CL01	Cold Room	9 m	17 m	3.5 kW

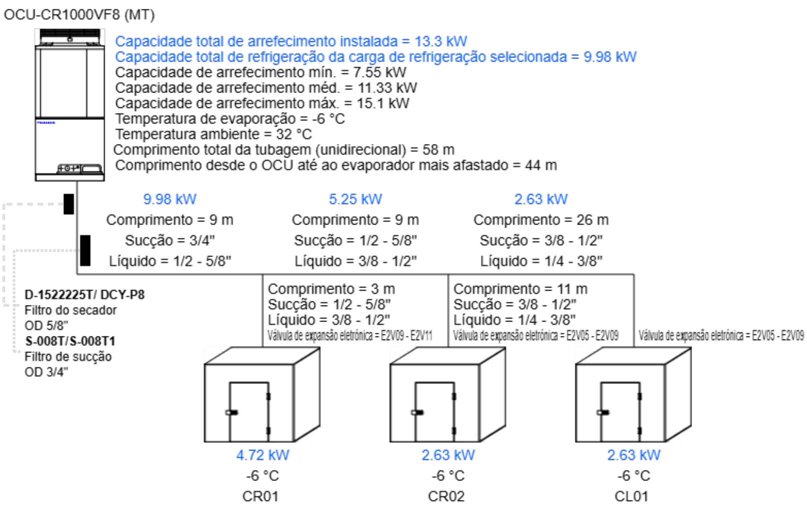

Figure B.3: Piping scheme for chilled storage rooms.

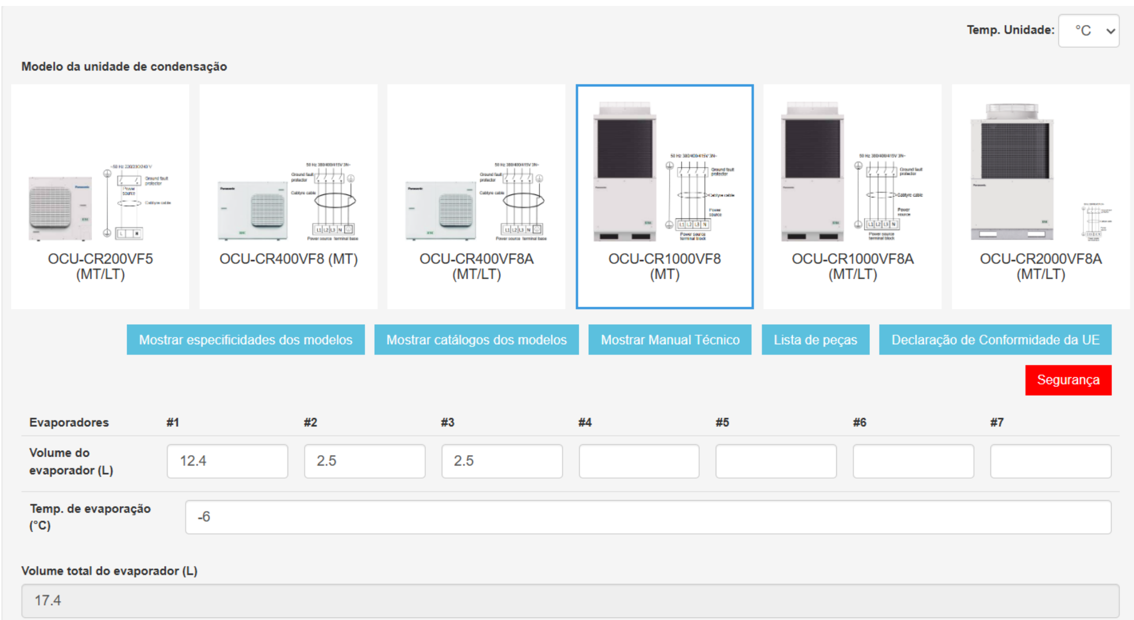

Figure B.4: RCU of the project.

Appendix C

Technical data

This appendix does respect to technical data from evaporators and display cabinets for the different supermarkets. All evaporators are from Supplier A.

C.1 Technical Data for Supermarket B

Table C.1: Technical data of cold storage room evaporators for Supermarket B (a).

Cold Storage Rooms	4.1.1	4.1.2	4.2.1	4.2.2	4.2.3	4.2.4
Refrigeration Temperature	Negative	Negative	Positive	Positive	Positive	Positive
Product Stored	Frozen Goods	Bakery Goods	CDN	Dairy Products	Butchery	Fish
Evaporator Model	DD/E 7C2/6 IQ CO2/45bar	DD/E 7C2/5 IQ CO2/45bar	BXN/E 230/49 ES CO2/60bar	BXN 330/74 ES CO2/60bar	BXN/E 230/49 ES CO2/60bar	16 ECT/E 26 CO2/60bar
Room Temperature [ºC]	-18/-20	-18/-20	+2/+4	0/+2	0	0
Room Volume [m^3]	48.8	38.0	32.5	44.9	25.3	40.8
Fan Motors						
Quantity	2	2	2	3	2	-
Total Absorbed Power [W]	70	70	70	105	70	-
Defrost						
Absorbed Power [kW]	2.4	2.4	1.8	natural	1.8	-
DEC [kWh/24h]	4.86	4.86	1.14	1.31	1.74	-

Note: For 4.2.4, the evaporator is a gravity coil so it runs only with natural convection. Therefore, there is no energy supplied for defrosting.

Table C.2: Technical data of cold storage room evaporators for Supermarket B (b).

Cold Storage Rooms	4.2.5	4.2.6	4.2.7	4.3.1	4.3.2	4.3.3
Refrigeration Temperature	Positive	Positive	Positive	Positive	Positive	Positive
Product Stored	Charcuterie	Chicken	Bakery	Garbage	Butchery Preparation	Charcuterie Prep
Evaporator Model	BXN 230/49 ES CO2/60bar	RWK/E 4A1/27 ES CO2/60bar	BXN/E 230/49 ES CO2/60bar	RWK 4A1/20 ES CO2/60bar	DFK 506 ES CO2/60bar	DFK 506 ES CO2/60bar
Room Temperature [ºC]	0/+2	0/+2	0	+2/+4	+8	+8
Room Volume [m^3]	45.0	11.0	22.3	37.8	38.6	31.6
Fan Motors						
Quantity	2	1	2	1	2	2
Total Absorbed Power [W]	70	35	70	35	68	68
Defrost						
Absorbed Power [kW]	Natural	1.2	1.8	-	-	-
DEC [kWh/24h]	0.88	1.02	1.74	0.42	0.82	0.82

Table C.3: Technical data of plug-in units for Supermarket B.

Plug-in Units	Various	Various	Various	3.3.3	3.3.8
Model	Expo	Paris	Paris	Repus 5 Codfish	Repus 5
Quantity	5	18	6	1	1
Used Refrigerant	R290	R290	R290	R290	R290
Refrigerant Max. Charge [kg]	0.75	2.34	0.66	0.15	0.15
TDA [m^2]	8.75	27.72	6.12	1.23	1.06
L [mm]	1500	2500	1854	900	937
Energy Consumption					
TEC [kWh/24h]	162.60	125.28	92.16	3.82	1.18

Table C.4: Technical data of display cabinets connected to central system for Supermarket B (a).

Display Cabinets	3.1.1	3.2.1	3.2.2	3.2.3	3.2.4	3.2.5
Refrigeration Temperature	Negative	Positive	Positive	Positive	Positive	Positive
Utility	fish	butchery	take-away	charcuterie	beverage	butchery
Model	SALO G4	REPUS 5	SM-REPUS 5-H16	SMHF-H12	OSAKA 3P 70H203	OSAKA 3P 70H203
Working Temperature [ºC]	-18/-21	-1/+1	0/+2	0/+2	0/+3	-1/+1
Quantity	2	1	2	2+2+4	1	1
TDA per unit [m^2]	2.78	2.88	5.99	2.20+2.23+2.94	2.10	6.30
L [mm]	2500	3750	3750	1875+1900+2500	1250	3750
Energy Consumption						
Evaporator consumption [W]	44	-	-	-	58	116
Defrost Power [kW]	1.95	-	-	-	natural	1.40
Defrost Time [h/day]	0.75	-	-	-	2	1.5
DEC [kWh/24h]	4.97	4.72	14.40	28.08	1.39	4.71

Table C.5: Technical data of display cabinets connected to central system for Supermarket B (b).

Display Cabinets	3.2.6	3.2.7	3.2.8	3.2.9	3.2.10	3.2.11
Refrigeration Temperature	Positive	Positive	Positive	Positive	Positive	Positive
Utility	yogurts	charcuterie	fruits/vegetables	miscellaneous	refrigerated products	take-away
Model	OSAKA 3P 70H203	OSAKA 3P 70H203	PANAMA 3P 100H203	OSAKA 3P 70H203	PANAMA 3P 70H203	OSAKA 3P 70H203
Working Temperature [ºC]	0/+2	0/+2	0/+2	0/+2	0/+3	0/+2
Quantity	1+4	1+1+1	1	2	1	1
TDA per unit [m^2]	3.15+6.3	3.15+4.2+6.3	6.58	4.2	3.15	4.2
L [mm]	1875+3750	1875+2500+3750	3750	2500	1875	2500
Energy Consumption						
Evaporator consumption [W]	58+116	58+58+116	152	58	58	58
Defrost Power [kW]	natural	natural	natural	natural	natural	natural
Defrost Time [h/day]	2	2	3.67	2	3.67	2
DEC [kWh/24h]	12.53	5.57	3.65	2.78	1.39	1.39

C.2 Technical Data for Supermarket C

C.2.1 Connected to CO_2 Central

TECHNICAL DETAILS **MAJA RVH**

Type	Ice output *) kg/24 h (1 h)	Fresh water consumption m^3/24 h	Refrigeration capacity required kW	Electrical connection 3AC/50Hz/400V/PE kW **)	Width mm	Depth mm	Height mm	Weight kg
RVH 250	250 (10)	0,25	t_O -20,0°C, 1,8	0,28	1045	512	525	90
RVH 400	400 (16)	0,40	t_O -20,5°C, 2,2	0,28	1185	512	525	115
RVH 800	800 (33)	0,80	t_O -21,5°C, 4,0	0,28	1345	512	525	140
RVH 1000	1.000 (41)	1,00	t_O -18,5°C, 5,6	0,28	1545	512	525	165
RVH 1500	1.500 (62)	1,50	t_O -18,5°C, 8,4	0,28	1695	512	525	175
RVH 2000	2.000 (83)	2,00	t_O -21,5°C, 11,5	0,28	1695	512	525	175
RVH 2500	2.500 (104)	2,50	t_O -21,5°C, 13,5	0,28	1695	512	525	175
RVH 3000	3.000 (125)	3,00	t_O -21,0°C, 16,2	0,34	1730	675	525	215
RVH 6000	6.000 (250)	6,00	t_O -22,0°C, 33,0	0,52	1860	1450	586	425
RVH 9000	9.000 (375)	9,00	t_O -22,0°C, 33,0 t_O -21,0°C, 16,2	0,52 0,34	1863	1456	1572	740
RVH 12000	12.000 (500)	12,00	t_O -22,0°C, 33,0 t_O -22,0°C, 33,0	0,52 0,52	1863	1456	1572	955

Figure C.1: Technical details of ice machine RVH 800.

Table C.6: Technical data of plug-in units for Supermarket C.

Plug-in Units	Bakery Cabinets	Wine Cooler	Promotional Islands	Fish
Model	DUKEL	MIAMI	EXPO	Repus II
Quantity	2	1	4	1
Used Refrigerant	R290	R290	R290	R290
Refrigerant Max. Charge [kg]	0.30	0.15	0.60	0.15
TDA [m^2]	-	0.64	7.00	1.23
L [mm]	1400	600	1500	900
Energy Consumption				
TEC [kWh/24h]	N.I.	4.56	130.08	18.29

Table C.7: Technical data of cold storage room evaporators for Supermarket C, CO_2 central.

Cold Storage Rooms	Frozen Room I	Frozen Room II
Refrigeration Temperature	Negative	Negative
Product Stored	Frozen Goods	Frozen Goods
Evaporator Model	BXL/E 230/38 CO2/45bar	BXL/E 225/24 CO2/45bar
Room Temperature [ºC]	-18/-20	-18/-20
Room Volume [m^3]	35.83	11.15
Fan Motors		
Quantity	2	2
Ttoal Absorbed Power [W]	70	68
Defrost (Electrical Type)		
Absorbed Power [kW]	1.8	1.32
DEC [kWh/24h]	3.96	3.20

C.2.2 Connected to R134a Central

Table C.8: Technical data of cold storage room evaporators for Supermarket C, R134a central (a).

Cold Storage Rooms	Butchery	Butchery Preparation	Garbage Room	Fresh Fish
Refrigeration Temperature	Positive	Positive	Positive	Positive
Evaporator Model	BXN/E 225/32	ERK 304/420	DF 5014	22 ECT/E 15
Room Temperature [ºC]	-1/+1	8	10	0
Room Volume [m^3]	11.40	13.33	24.70	26.55
Fan Motors				
Quantity	2	1	3	-
Total Absorbed Power [W]	180	72	210	Natural Convection
Defrost				
Absorbed Power [kW]	1.32	Natural	Natural	-
DEC [kWh/24h]	2.38	0.86	2.52	-

Table C.9: Technical data of cold storage room evaporators for Supermarket C, R134a central (b).

Cold Storage Rooms	Charcuterie	Chilled Room	Vegetables and Fruit
Refrigeration Temperature	Positive	Positive	Positive
Evaporator Model	BXN 230/49	DF/E 5014 + TA/E 2316	ERK 304/413
Room Temperature [ºC]	0/+2	0/+2	8
Room Volume [m^3]	22.10	37.28	12.00
Fan Motors			
Quantity	2	3+3	1
Total Absorbed Power [W]	240	210+114	72
Defrost			
Absorbed Power [kW]	Natural	3.2+1.6	Natural
DEC [kWh/24h]	3.00	6.29	0.86

Appendix D

IPMA Weather Report

IPMA

RESUMO MENSAL– ABRIL

Tabela. *Resumo mensal relativo às capitais de Distrito*

Estação Meteorológica	TN	TX	TNN	D	TXX	D	RR	RRMAX	D	FFMAX	D
Viana do Castelo	10.1	20.2	4.3	29	27.3	12	74.8	16.4	08	65.2	02
Braga	9.0	23.0	2.8	29	30.9	12	98.9	24.3	30	61.6	02
Vila Real	7.9	20.2	1.6	09	28.5	12 e 13	66.2	15.0	02	46.1	02
Bragança	5.7	19.4	0.6	23	28.4	13	38.8	11.4	08	62.6	02
Porto/P. Rubras	11.4	20.5	6.1	09	28.5	11	78.7	14.9	08	65.9	02
Aveiro	11.6	20.6	6.8	09	28.2	11 e 12	63.3	16.6	20	61.9	01
Viseu	8.4	19.7	2.9	09	29.6	12	61.4	20.9	08	56.5	01
Guarda	6.4	16.1	0.4	09	25.5	12	49.7	10.6	07	60.8	02 e 08
Coimbra/Cernache	10.8	22.1	5.3	09	29.6	14	48.9	12.0	26	63.4	02
Castelo Branco	10.2	21.7	4.0	28	28.8	16	25.2	5.9	07	64.4	08
Leiria	9.0	22.5	4.1	09	31.1	14	42.7	10.9	27	53.3	05
Santarém	11.2	24.2	7.4	09	33.1	14	17.9	5.2	02	58.7	02
Portalegre	11.7	20.7	5.0	09	27.8	13 e 14	51.3	13.1	20	70.2	23
Lisboa/G.Coutinho	12.9	22.3	9.2	09	29.5	14	18.7	10.8	02	62.6	02
Setúbal	10.1	22.9	5.1	28	30.0	11	15.6	8.3	02	42.8	08
Évora	9.0	23.0	4.5	28	28.5	14	27.3	7.1	08	52.6	26
Beja	10.1	23.2	5.2	29	28.8	17	20.2	6.0	07	53.3	05
Faro	13.7	22.1	9.1	09	29.3	15	5.3	2.1	26	54.4	27

Legenda

TN Média da temperatura mínima (Graus Celsius)

TX Média da temperatura máxima (Graus Celsius)

Figure D.1: IPMA weather report for April 2024.

Appendix E

Spreadsheet for TEWI of Supermarkets

E.1 Supermarket B

Figure E.1 illustrates the spreadsheet used to calculate the TEWI of the installation.

TEWI CALCULATION		
System Operating Lifetime (n)	15	
Indirect Emission Factor (β)	0.141	[kg CO2e/kWh]
Recovery Factor (α)	0.70	

Centralized System	Yes	
Refrigerant	R744	
GWP	1	
Annual Leakage Rate (Lannual)	75	[kg/year]
Refrigerant Charge (m)	150	[kg]
Annual Energy Consumption (Eannual)	247762.7	[kWh/year]

Centralized System		
Indirect Emissions	524018.11	[kg CO2e]
Direct Emissions	1170.00	[kg CO2e]
TEWI	525188.11	[kg CO2e]

TEWI of installation	525191.8	[kg CO2e]
	525.2	[ton CO2e]

Plug-in Units	Yes	
Refrigerant	R290	
GWP	3	
Annual Leakage Rate (Lannual)	-	[kg/year]
Refrigerant Charge (m)	4.05	[kg]
Annual Energy Consumption (Eannual)	-	[kWh/year]

Plug-in Units		
Indirect Emissions	-	[kg CO2e]
Direct Emissions	3.65	[kg CO2e]
TEWI	3.65	[kg CO2e]

Remote Condensing Units	No	
Refrigerant	-	
GWP	-	
Annual Leakage Rate (Lannual)	-	[kg/year]
Refrigerant Charge (m)	-	[kg]
Annual Energy Consumption (Eannual)	-	[kWh/year]

Remote Condensing Units		
Indirect Emissions	-	[kg CO2e]
Direct Emissions	-	[kg CO2e]
TEWI	-	[kg CO2e]

Figure E.1: Spreadsheet for TEWI of Supermarket B.

In more detail, Figure E.2 shows the inputs entered for the centralized system and the store's plug-in units. The value of the energy consumed entered corresponds to the total value during one year

TEWI CALCULATION		
System Operating Lifetime (n)	15	
Indirect Emission Factor (β)	0.141	[kg CO2e/kWh]
Recovery Factor (α)	0.70	
Centralized System	Yes	
Refrigerant	R744	
GWP	1	
Annual Leakage Rate (Lannual)	75	[kg/year]
Refrigerant Charge (m)	150	[kg]
Annual Energy Consumption (Eannual)	247762.7	[kWh/year]
Plug-in Units	Yes	
Refrigerant	R290	
GWP	3	
Annual Leakage Rate (Lannual)	-	[kg/year]
Refrigerant Charge (m)	4.05	[kg]
Annual Energy Consumption (Eannual)	-	[kWh/year]
Remote Condensing Units	No	
Refrigerant	-	
GWP	-	
Annual Leakage Rate (Lannual)	-	[kg/year]
Refrigerant Charge (m)	-	[kg]
Annual Energy Consumption (Eannual)	-	[kWh/year]

Figure E.2: Inputs for spreadsheet of Supermarket B.

Figure E.3 illustrates the values of direct and indirect emissions for each subsystem, with the centralized system being responsible for almost all direct emissions of the installation. TEWI of this supermarket is 525.2 tonnes of CO_2 equivalent.

Centralized System					
Indirect Emissions	524018.11	[kg CO2e]			
Direct Emissions	1170.00	[kg CO2e]			
TEWI	525188.11	[kg CO2e]			
			TEWI of installation	525191.8	[kg CO2e]
				525.2	[ton CO2e]
Plug-in Units					
Indirect Emissions	-	[kg CO2e]			
Direct Emissions	3.65	[kg CO2e]			
TEWI	3.65	[kg CO2e]			
Remote Condensing Units					
Indirect Emissions	-	[kg CO2e]			
Direct Emissions	-	[kg CO2e]			
TEWI	-	[kg CO2e]			

Figure E.3: Outputs for spreadsheet of Supermarket B.

E.2 Supermarket C

The data used to fill the spaces of spreadsheet of Supermarket C (Figure E.4) are related to plug-in units and a centralized cascade system with two cycles. Each cycle has to have its own calculations related to its refrigerant properties but TEWI for indirect emissions was all calculated at once.

TEWI CALCULATION		
System Operating Lifetime (n)	15	
Indirect Emission Factor (β)	0.141	[kg CO2e/kWh]
Recovery Factor (α)	0.70	
Centralized System	Yes	

Negative Refrigeration Cycle		
Refrigerant	R744	
GWP	1	
Annual Leakage Rate (Lannual)	45	[kg/year]
Refrigerant Charge (m)	170	[kg]
Annual Energy Consumption (Eannual)	-	[kWh/year]

Positive Refrigeration Cycle		
Refrigerant	R134a	
GWP	1430	
Annual Leakage Rate (Lannual)	110	[kg/year]
Refrigerant Charge (m)	300	[kg]
Annual Energy Consumption (Eannual)	468068.0	[kWh/year]

Plug-in Units	Yes	
Refrigerant	R290	
GWP	3	
Annual Leakage Rate (Lannual)	-	[kg/year]
Refrigerant Charge (m)	1.2	[kg]
Annual Energy Consumption (Eannual)	-	[kWh/year]

Remote Condensing Units	No	
Refrigerant	-	
GWP	-	
Annual Leakage Rate (Lannual)	-	[kg/year]
Refrigerant Charge (m)	-	[kg]
Annual Energy Consumption (Eannual)	-	[kWh/year]

Figure E.4: Inputs for spreadsheet of Supermarket C.

In turn, Figure E.5 demonstrates the results obtained for the emissions of this facility, which are very high in comparison with the other supermarkets, having high values for both direct and indirect emissions due to the centralized system, with a TEWI for Supermarket C of 3,478.9 tonnes of CO_2 equivalent.

Centralized System (Negative)		
Indirect Emissions	-	[kg CO2e]
Direct Emissions	726.00	[kg CO2e]
TEWI	726.00	[kg CO2e]

Centralized System (Positive)		
Indirect Emissions	989963.82	[kg CO2e]
Direct Emissions	2488200.00	[kg CO2e]
TEWI	3478163.82	[kg CO2e]

TEWI of installation	3478890.9	[kg CO2e]
	3478.9	[ton CO2e]

Plug-in Units		
Indirect Emissions	-	[kg CO2e]
Direct Emissions	1.08	[kg CO2e]
TEWI	1.08	[kg CO2e]

Remote Condensing Units		
Indirect Emissions	-	[kg CO2e]
Direct Emissions	-	[kg CO2e]
TEWI	-	[kg CO2e]

Figure E.5: Outputs for spreadsheet of Supermarket C.