Choosing an optimized refrigeration system based on sustainability and operational scenarios applied to four supermarket architectures in three European countries

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Abstract

The growing global demand for refrigeration requires the design of more sustainable systems. However, despite environmentally promising technologies in refrigeration, there are still barriers to their widespread adoption. In this paper, a generic approach able to describe the multiple performances (energy, environmental, economic, social) of refrigeration systems is proposed to assess their potential of adoption. To propose a realistic study framework, four architectures of supermarket refrigeration systems are modelled and simulated using ground data with different climatic conditions and electricity mixes (France, Sweden, Spain). The overall results of these operational scenarios show that the electricity mix is the most influential parameter on cost and environmental impact. In addition, architecture using CO_2 refrigerant shows interesting performances regardless of location and despite degraded regimes during heat peaks. However, the maintenance score can be a limiting factor for installing more energy efficient systems. Two other scenarios are studied: with photovoltaic panels; with financial support. Photovoltaic panels help improving cost and environmental performances, but also strongly depend on maintenance performances. Financial support helps facilities using low-global-warming-potential refrigerant to be more competitive than those using high-global-warming-potential refrigerant.

Highlights

- A multi-criteria approach is proposed to help choosing refrigeration system design
- The method is based on process engineering and industrial engineering approaches
- Four refrigeration architectures are tested with realistic data in three countries
- CO_2 systems are relevant for several performances but trade-offs must be made
- Impact of PV panels and financial support on performances are assessed

Keywords: sustainability, refrigeration, decision making, design, supermarket

Nomenclature

GWP	Global Warming Potential
$\dot{Q}_X$	Heat flows
$\dot{W}_x$	Compressor power
Δt_x	Functioning hours
E_{si}	Electric consumption
COP	Coefficient of performance
T_x	Temperature
η	Efficiency
LCCP	Life cycle climate performance
DE_m	Direct emissions
EE_m	Embodied emissions
IE_m	Indirect emissions
TCO	Total cost of Ownership
$CAPEX$	Capital costs
$OPEX$	Operational costs
C_x	Costs of component x
n	Life time
m_x	Mass of component x

1. Introduction

In recent decades, the world has been increasingly affected by climate change. According to Intergovernmental Panel on Climate Change (IPCC), annual greenhouse gas emissions increased by 80 % between 1970 and 2014 (Blanco *et al.* 2014). Through the Montreal protocol in 1987 and Kigali amendments in 2005 and 2016 (Heath 2017; USCFR 1993), the refrigeration industry has been concerned with the environmental issues, banning ChloroFluoroCarbons (CFCs) refrigerants, responsible for the ozone layer depletion, and reducing the use of high Global Warming Potential (GWP) HydroFluoroCarbons (HFCs). However, rising temperatures have increased the need for refrigeration in the food sector, pharmaceuticals, buildings and transport (Schaeffer *et al.* 2012), as well as extreme events such as heat waves and recent pandemics. Today, nearly 20 % of all electricity consumption is used for cold production. This figure is expected to rise with growing demand and is predicted to reach 37 % by 2050 (IEA 2018).

In this context, academics and industry have conducted research to develop more sustainable solutions, such as improving the energy efficiency of refrigeration equipment or limiting the use of HFCs. After the International Energy Agency (IEA 2020), such solutions could reduce warming by 0.5 °C by 2100. Nevertheless, technological improvement of refrigeration equipment is an essential lever in the fight against climate change, but not sufficient. Indeed, energy-promising technologies can also be more complex to implement in the industry, which is a barrier to their adoption. As highlighted by de Paula *et al.* (2020), most papers compare energy/exergy performances using simplified steady-models. Moreover, experimental work is generally carried out under controlled laboratory conditions (Ben-Abdallah *et al.*, 2019). Thus, most studies show the intrinsic value of new technologies, without accounting for the complexity of realistic industrial conditions, nor the impact that the technology may cause. For example, the use of new fluids (Adebayo *et al.*, 2021), the combination of refrigeration cycles (Zhou *et al.*, 2022) or the addition of thermal energy storage (Xu *et al.*, 2019) theoretically improves the carbon footprint of facilities, but usually requires architectural changes, which can slow down their implementation.

In addition, the complexity of technologies can change over time. For example, early studies on CO_2 refrigerant showed difficulties at ambient temperature above 25 °C (Finckh *et al.*, 2011). The latest studies show good performances in all weather conditions (Sun *et al.* 2020). However, new CO_2 systems are more complex, while it is already difficult for companies to adapt to the CO_2 operation of “old” systems. This requires additional trainings and certifications for operators and designers. This constraint must also be taken into account for the adoption of innovative technologies in industrial environments.

Finally, a multi-criteria approach, such as 4E - Energy, Exergy, Economic and Environmental (Yu *et al.*, 2022), is needed to assess the performance and adoption difficulties of new technologies. Yang et al. (2021) developed a multi-optimisation method based on the evaluation of the energy, economic and environmental performance of a novel hybrid system to assess the potential of such technology. They thus manage to offer design changes to reduce energy consumption and overall costs. In the literature, there is a growing number of studies on energy and thermo-economic performances to integrate technology complexity. Glavan *et al.* (2016) proposed a model for predicting the performance of a transcritical CO_2 system, validated by field measurements. They show a good adequacy of the model which could be used to design a system configuration or to optimise the control strategy of the machines. Azzolin et al. (2021) have tested seven configuration of CO_2 transcricial systems for supermarket in Italy, considering the external temperature. They have found that hot climate conditions during summer significantly impact the system efficiency. D'Agaro *et al.* (2019) propose a model for optimising the overall costs of the refrigeration system and food quality by varying several parameters, such as defrost, filling with the products or consumer behaviour. Other complex technologies are studied in the literature through exergy and energy detailed modelling. For example, Razmi et al. (2018) studied a hybrid absorption/compression system to improve the efficiency of the system, by integrating a compressor between the generator and the condenser coils. They show that the efficiency can be almost four times higher than a conventional system. They completed this work by an economic study, showing that this system could have a payback of four years in their application conditions (Razmi et al. 2020). However, these studies do not consider the consequences of this integration on the ground (space needed, accessibility) and the complexity of the market (multiplicity of stakeholders). Moreover, these studies are generally conducted by numerical simulation and focus on the demonstration of a particular technology, but the generality of those models is not sufficient to be applied to different industrial environments. For example, if operators are not trained in CO_2, is this climate-friendly technology under laboratory conditions still socio-economically acceptable?

It is thus necessary to consider at the same time new technology and socio-economic environment complexity in effective industrial implementation. To our knowledge, users (engineers, designers, decision makers) lack a complete view of the performance of a refrigeration system, as highlighted in previous ground diagnosis (Salehy *et al.* 2021). Moreover, although today human decision-making and learning are greatly enhanced by digital tools, this improvement is effective only if sufficient interpretable data are provided to the user. Industrial performance benchmarks are therefore necessary to compare technologies in real conditions before deciding to develop one. Aggregating industry performance into a single analysis, such as ease of maintenance, technological maturity, detailed life-cycle energy and economic costs, and environmental impacts, could thus enable industrial stakeholders to better understand the potential of innovative technologies in a more realistic decision context (Brom *et al.* 2016).

To address this issue, the present work aims to provide a generic approach able to describe the complexity of the socio-economic environment for various refrigeration applications. Thus, the potential adoption of innovative technologies could be assessed under realistic industrial conditions. The originality of this paper stands in several points: the methodology based on two disciplines; the type of performances used; the case studies involving four architectures in three countries:

- The methodology is based on classical process engineering approach to evaluate the performance of refrigeration systems, but structured in a research framework from industrial engineering, namely knowledge model or framework. The knowledge model is a formalisation of the decision steps, based on problem definition and performance evaluation. This multi-disciplinary approach is original in the context of refrigeration system assessment.

- The studied performances include the three pillars of sustainable development (Purvis *et al.*, 2019), environmental, economic, and social. The social is assessed for the first time for refrigeration systems using industrial engineering knowledge, such as analysis of qualitative maintenance, ergonomics, and risk.
- To illustrate the approach, a case study of supermarket refrigeration systems is used. Four configurations are tested using realistic data in three countries (Sweden, France, Spain) and refrigeration system design's data from manufacturer and literature, which is an original case study in the literature. The configurations and locations chosen depend on several criteria: first, the systems modelled in this study correspond to an overview of several types of architecture (direct or indirect) that are usually found in supermarkets; second, in order to observe different climates, three types of climates that occur in Europe are tested: a "cold" climate (Sweden), a temperate climate (France) and a hot climate (Spain). Nevertheless, these three European countries meet the same regulations and have similar design parameters (same suppliers, same market, same price range).

The ultimate objective of this generic yet realistic approach is to help manage research and development (R&D) and decision making for the implementation of more sustainable technologies.

2. *Modelling method*

To ensure better adoption of new technologies through a better understanding of their operation in an industrial space, a knowledge framework was developed to describe the multi-performance evaluation of refrigeration systems.

This framework follows the usual steps of a design process from the definition of the design problem (here the cold need specification) to the design decision based on the refrigeration system performance analysis (Pahl and Beitz 2013):

- First step: *design problem definition*, also called task clarification, where the system environment and the related requirements (here cold needs) are defined.
- Second step: definition of the feasible solutions, i.e. the system structure with architecture, combination of components and technological innovative clusters, called *conceptual design*.
- Third step: performance assessment of feasible solutions, called *embodiment design*, using mathematical models to link different criteria or performances to each other. In the present model, four categories of performance are evaluated throughout the lifecycle: energy, environmental, economic, and social. This last performance involves the evaluation of operational/industrial conditions according to the system configuration.

Finally, one of the goals of the knowledge framework is to highlight the need for trade-offs in scenarios using real supermarket data. The overview of this knowledge framework is presented in Figure 1.

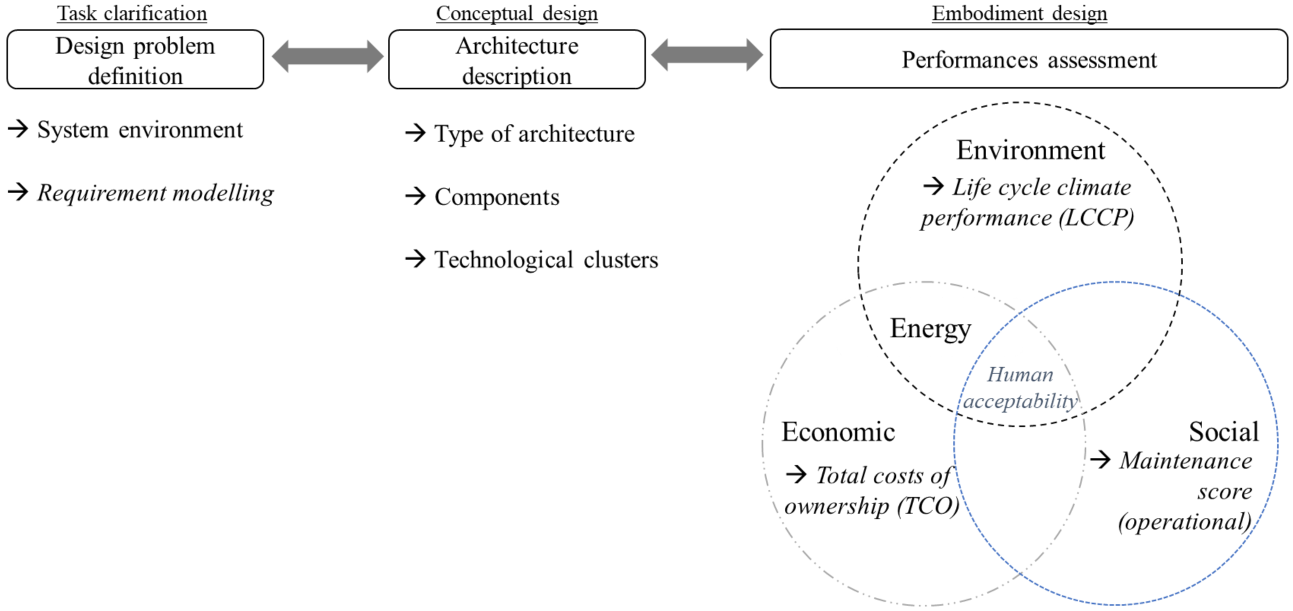


Figure 1. General overview of the process

2.1. Design problem definition

The design problem is defined in engineering design as the representation of the problem scope to be investigated to find a design solution (Gero, 1990). For this purpose, the system environment must first be described as well as the modelling requirements and assumptions.

2.1.1. System environment description

In the present model, the system environment includes all operational conditions necessary to calculate the refrigeration requirements of the supermarket. It is composed of fourteen variables (Table 1) related to food preservation: location, supermarket (store area, opening hours, number of employees), cold room (or display cabinets), defrost.

It is possible to add/remove variables for other different design problem. For example, if the objective is to model an air conditioning system for a supermarket, the design problem definition should include in the system environment such as the sizing of the store wall and their material composition, the number of clients, the lights in the building.

Table 1. System environment variables used for retail refrigeration systems. The data describing the supermarket are taken from the ADEME and Enertech report (2001)

Variable name	*Description*	*Data used in this article*
Loc_{store}	Store location	Paris/Toledo/Stockholm
T_{ext}	External temperature	

$T_{ambiance}$	Temperature inside the store	20 °C from October to April 25 °C from May to September
OpeningHour	Opening hour (for customers)	12 hours
WorkingHour	Working hour (for employees)	16 hours
M_{fpos}	Mass of food stored in refrigeration (positive temperature)	[30;1,000] kg
$T_{pos\_setpoint}$	Positive temperature range for food refrigeration storage	[0;3] °C
PosDisplayCabinet*	Number of positive temp display cabinets	25
PosColdRoom	Number of refrigerated cold storage room	1
M_{fpos}	Mass of frozen food stored (negative temperature)	[30;1,000] kg
$T_{neg\_setpoint}$	Negative temperature range for frozen food storage	[-18;-20] °C
NegDisplayCabinet*	Number of negative temp display cabinets	8
NegColdRoom	Number of frozen cold storage rooms	1
Nd	Number of doors opening	
n	System lifetime	10 years

** If it is unknown, a land occupation rate can be used.*

2.1.2. Modelling requirement

For the calculation of the requirements, here the cooling power, some assumptions are taken:

- Temperature and relative humidity inside the store are constant (20 °C from October to April; 25 °C from May to September; 60 % of relative humidity)
- Heat losses in pipes are neglected
- In secondary loop system, heat exchanger pinch is 10 °C
- Superheating (evaporator) is 5 °C and subcooling (condenser) is 10 °C
- Annual outdoor temperature and humidity profile depends on the location
- Air conditioning and heater models are not displayed in this paper to facilitate understanding of the overall methodology and result analysis. However, the methodology framework allows additional requirements (air conditioning, heater) to be included.
- Fruits and ice cream are considered respectively for refrigerated and frozen food.

The system environment variables from Table 1 allow the cooling power for each cold room or display cabinet to be calculated. These data are then added together to calculate the supermarket's cooling requirement (only for food preservation). Finally, the required cooling capacity is increased by approximately 30 % to follow industrial practices. For example, for a cold need of 30 kW, the industrialist would purchase a compressor with a maximum cooling capacity of 39 kW to account for error estimations or abnormal peak demands.

The cooling power, in display cabinets (DC) and cold room (CR), can be calculated using following heat balances:

$$\dot{Q}_{DC\ or\ CR} = \dot{Q}_{wall} + \dot{Q}_{food} + \dot{Q}_{lighting} + \dot{Q}_{infiltration\_day} + \dot{Q}_{radiation\_day} + \dot{Q}_{fan} + \dot{Q}_{peop} \quad (1)$$

Where $\dot{Q}_X$ (W) is the heat flows involved (generated, undergone) for various elements x of DC: wall, food, lightning, infiltration, radiation, fans and people. From the supermarket case study and the validation scenario, the data for the fan and the lightning are based on the 2001 ADEME and Enertech report (2001): $\dot{Q}_{fan} = 150\ W/DC\ or\ 30W/m^2 in\ CR$; $\dot{Q}_{lighting} = 288\ W/DC\ or\ 10W/m^2 in\ CR$ (each cabinet is 2.5 m long, with 8 x 36W lighting tubes).

2.2. Conceptual design and architecture description

The conceptual design step defines the structure and technical components necessary to compose a refrigeration system. For negative and positive temperatures (< and > 0 °C), the refrigeration system modules are the same for the main components (compressor, condenser, evaporator, expansion valve, refrigerant and pipes). The structure and component variables in a supermarket case study are presented in Table 2. Depending on the architecture, specific components may be used, such as CO_2 supporting components for transcritical architectures. Other design constraints are defined as incompatibilities (Bussemaker, *et al.* 2020).

In addition, an extra technological cluster can be added in the structure. A cluster is defined here as an innovative sub-system that could improve the sustainability of an architecture. This addition changes the system structure (configuration) of an architecture for this conceptual design step and impacts the next embodiment design step.

Table 2. Refrigeration system decomposition in the model for retail application

Main category	Sub-category	Description	Compatibilities
System structure	Architecture	Architecture determining component used, machine location, space used, pipelines length, etc.	No conditions
Technical modules	Compressor	For positive/negative temperature	With refrigerant and architecture
	Condenser	For positive/negative temperature	With compressor
	Evaporator	For positive/negative temperature	With the type of conservation (DC/CR)

	Expansion valve	For positive/negative temperature	With the number of evaporators
	Refrigerant	For positive/negative temperature; substance used in a (refrigeration) thermodynamic cycle with gas/liquid or liquid/gas phase change	With set-point temperature With the regulation
	Specific components	Used for particular architecture (Circulation pump, heat exchangers)	
	Pipelines	To transport refrigerant/secondary fluid (suction/discharge)	Pipeline diameters must fit to entry/exit of technical modules.
System structure or technical module	Technological Cluster	Innovative sub-system	Must be integrated in the architecture

In the present article, four types of architecture for food preservation are explored: centralized direct expansion system; secondary loop system; CO_2 transcritical booster system; plug-in system. Each architecture presents advantages and drawbacks, depending on their performances and the knowledge of the operators, which allows various scenarios to be compared.

2.2.1. Centralized direct expansion system

Most supermarkets use centralized direct expansion system where cold production is connected to the entire store through a piping system that transports the refrigerant to all the evaporators in the display cabinets and cold rooms. The cold production is usually located in a machine room, separated from the display cabinets. A centralized system operates with multiple compressors to achieve the required cooling capacity. The result of this arrangement can be unused compressor capacity if the system is oversized. In the present paper, the refrigerant tested are R404a and a low-GWP substitute R1234yf. Figure 2.a represents a simplified scheme of the modelled centralized system (without fans and control components).

2.2.2. Secondary loop system

Secondary loop refrigeration systems, also known as “Liquid-Chilling Systems” (ASHRAE 2008), are frequently used in industrial refrigeration and commercial comfort cooling. This architecture was first introduced to limit the use of refrigerants (toxicity/flammability, high GWP). It is composed of two loops (Figure 2.b). The primary loop, a direct expansion system using a primary refrigerant, cools a secondary fluid in a secondary loop via a heat exchanger (Wang *et al.* 2010). This secondary fluid provides the cooling capacity through heat exchangers in cold rooms and display cabinets, instead of traditional evaporators.

SL allows the containment of the primary loop and the use of climate-friendly secondary refrigerants (also known as heat transfer fluids). It reduces then the amount of primary refrigerant charge and the refrigerant leakage due to shorter circuits. In the present study, the primary refrigerants are R404a and R717. The service and maintenance are easier than a primary centralized system (Horton 2004). The additional cost of the pumps and heat exchanger could be offset by reducing refrigerant charge and copper pipe length (by using plastic pipe for the secondary loop) (DelVentura *et al.*, 2007). Kazachi and Hinde (2006) compared a secondary loop system and a traditional direct expansion system in a supermarket. They confirmed the advantages presented above and identified one disadvantage: additional energy consumption due to the intermediate circulation pumps and heat exchanger.

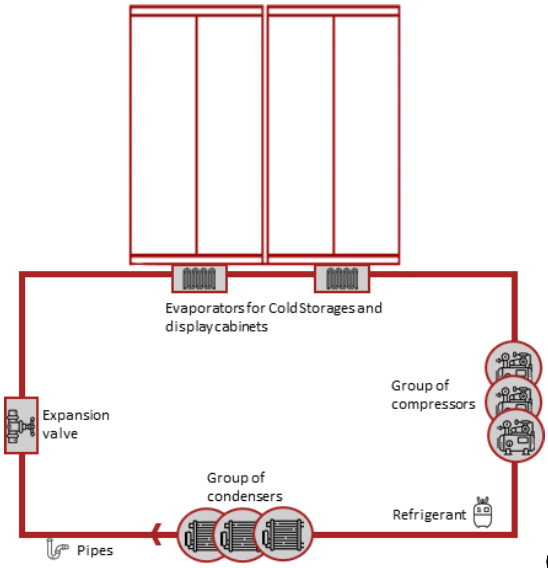
2.2.1. *CO_2 transcritical booster system*

Due to their lower environmental impact than conventional systems, "natural" refrigerants CO_2 or R744 (GWP = 1; Ozone Depletion Potential-ODP = 0) have been extensively investigated and developed (He *et al.* 2017). CO_2 system is also economically attractive with no limitations due to regulations except pressure levels. It is considered as one of the most viable solutions for supermarket (Lorentzen, 1994).

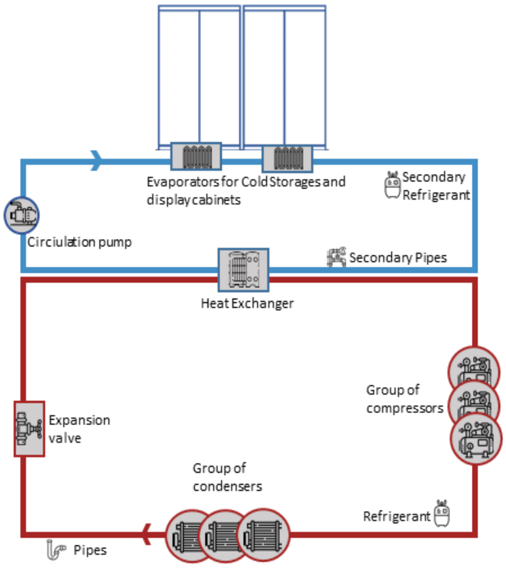
CO_2 booster or transcritical refrigeration system has been applied in modern supermarkets as a substitute for conventional R404A systems. In the present article, a typical CO_2 transcritical refrigeration system is modelled based on the one presented by Ge and Tassou (2011b). This architecture (Figure 2.c) presents multiple pressure sections with various compressor components, gas cooler or condenser depending on ambient conditions, heat exchangers and control valves.

2.2.2. *Plug-in system (PI)*

PI refrigeration unit (Figure 2.d) is a direct expansion system with: compressor, condenser, expansion valve and evaporator included in a cabinet. This is a major advantage as it provides the supermarket a greater flexibility in arrangement of cabinets. Besides no machine room is needed and the installation is less complex. However, there are several disadvantages: noise nuisance, higher energy consumption for air conditioning in summer due to the heat rejected by the plug-in units.



(a)



(b)

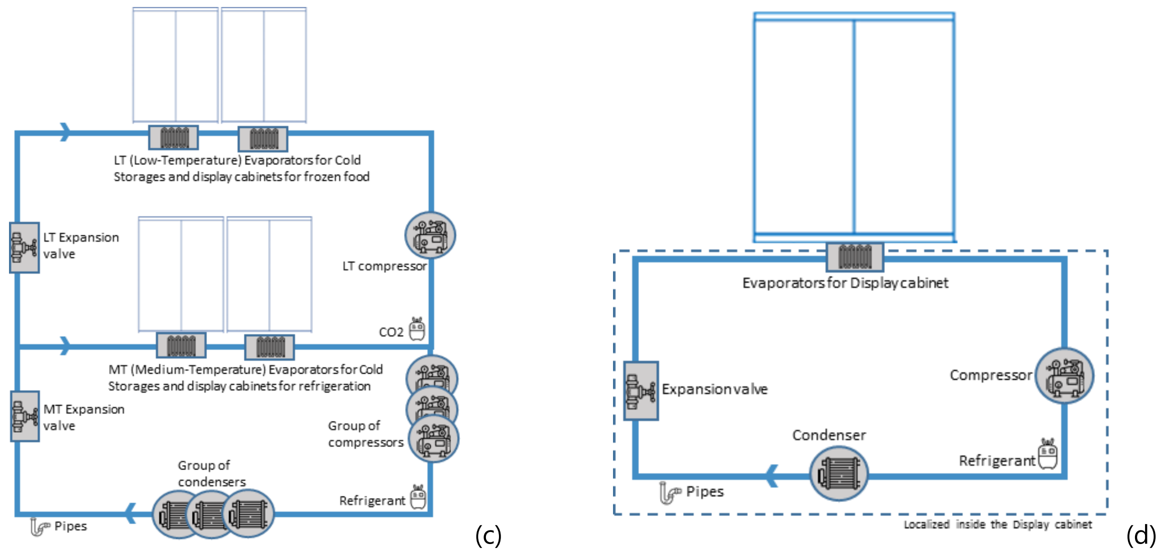


Figure 2. Simplified schemes of the architectures: (a) centralized direct expansion system; (b) secondary loop refrigeration system; (c) transcritical system; (d) plug-in cabinet

2.3.Embodiment design: Performance assessment

To assess how a solution fits to one scenario and compare among design solutions, various performances are modelled: energy consumption; environmental impact (Life Cycle Climate Performance – LCCP); financial cost (Total Cost of Ownership – TCO); and maintenance score. As in industrial design approach, the performance analysis is based on the manufacturer's data when available, and on the choice and the sizing of components according to the cooling requirement. Performance modelling steps are illustrated in Figure 3 and detailed in following sections. It should be noted that energy performance is used as an input for both environmental impact and financial cost.

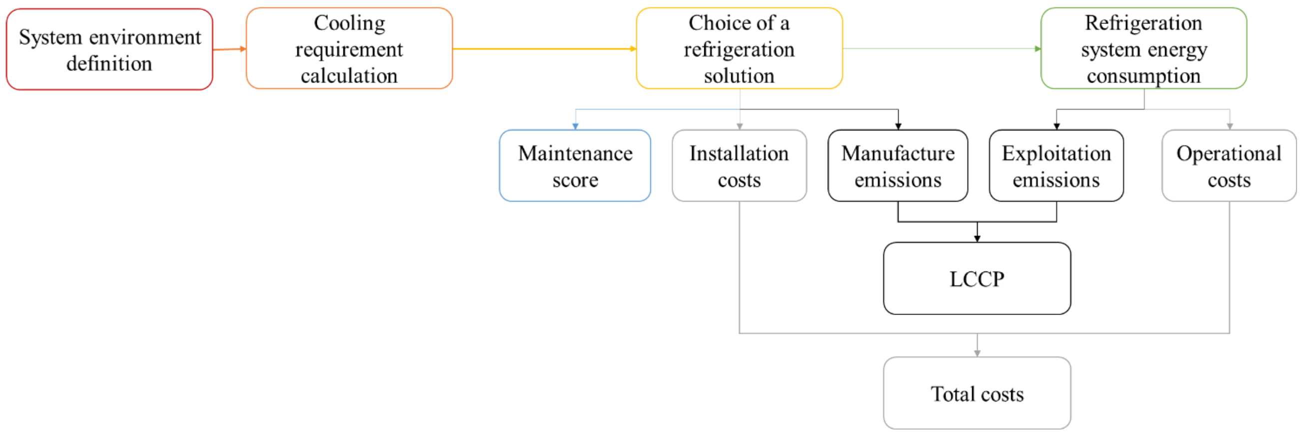


Figure 3. General overview of the system performance modelling

2.3.1. Energy consumption

Based on (Ge and Tassou 2011a) hypothesis, the total energy consumption of a refrigeration system in a supermarket is the sum of the consumption of various subsystems:

$$E_{sys} = \sum_i E_{si} \tag{2}$$

Where E_{si} is the consumption of a subsystem *i* such as display cabinets and cold rooms. E_{sys} can be evaluated for different time scales: yearly, monthly or daily.

For a daily energy consumption, E_{si} (kWh/day) is calculated as follows:

$$E_{si} = \dot{W}_{comp\_day} * \Delta t_{OH} + \dot{W}_{comp\_night} * \Delta t_{CH} + \dot{Q}_{defrost} * \Delta t_{defrost} + E_{cluster} \tag{3}$$

Where Δt_{OH} and Δt_{CH} the opening and closing hours of the store; $\dot{Q}_{defrost}$, defrost energy and $\Delta t_{defrost}$ defrost time; $E_{cluster}$ energy consumption added or gained by a potential technological cluster, for example an additional power generation system.

And where

$$\dot{W}_{comp\_day} = \frac{\dot{Q}_r}{COP} \tag{4}$$

With $\dot{W}_{comp\_day}$ the energy consumption by the compressor in kW; $\dot{Q}_r$ the cooling power from equation (1).

And the coefficient of performance (COP) of the refrigeration system is defined as:

$$COP = COP_{theorical} * \eta \tag{5}$$

With η the efficiency of the compressor based on manufacturer data. In this paper, compressor irreversibility is indeed taken into account in this efficiency, as well as pinch in evaporator/condenser (in the following), and subcooling/superheating (included in cooling power). On the other hand, other irreversibilities such as pressure drop or non-isentropic expansion are not considered.

The theoretical COP, which is related to the cooling power $\dot{Q}_r$, the compressor power $\dot{W}_{comp\_day}$, and consequently the power at the condenser, is equal to:

$$COP_{theorical} = \frac{T_c}{T_h - T_c} \tag{6}$$

With $T_c = T_{set\ point} - Pinch_c$ and $T_h = T_{outside} + Pinch_h$. $Pinch_c$ and $Pinch_h$ are respectively the difference between the air temperature and the evaporating or condensing temperature, based on manufacturer data. For this study, the following values are used: $Pinch_c = 5\ °C$; $Pinch_h = 10\ °C$.

2.3.2. Environmental impact

To assess the environmental impacts of the refrigeration system, the chosen method is Life Cycle Climate Performance (LCCP), characterising the global emissions of a refrigeration system during its whole lifecycle

(Hwang et al. 2015):

$$LCCP = \sum DEm + \sum IEm + \sum EEm \quad (7)$$

With DEm the direct emissions; IEm the indirect emissions; EEm the embodied emissions.

In this study, LCCP is expressed in $kgCO_{2eq}$, without considering other categories of environmental impacts such as ozone depletion or eco-toxicity.

The direct emissions (Eq 8) are the sum of the emissions related to the refrigerant leakage occurring during the exploitation phase, also called Middle Of Life (MOL), and the end-of-life (EOL) treatment phases, respectively Eq (9) and (10), where m_{ref} is the refrigerant mass in the whole system, n is the system lifetime, $leak_{ref_{year}}$ and $leak_{ref_{EOL}}$ are respectively the percentage of leakage depending on the system architecture per year during MOL and EOL, $CO_{2\,eq\_ref}$ is the global warming potential (GWP) of the refrigerant. If a technological cluster is added in the model, the direct emissions linked to the cluster are added ($DEm_{cluster}$).

$$\sum DEm = DEm_{refleak,MOL} + DEm_{refleak,EOL} +/- DEm_{cluster} \quad (8)$$

$$DEm_{refleak,MOL} = m_{ref} * n * leak_{ref_{year}} * CO_{2eq\_ref} \quad (9)$$

$$DEm_{refleak,EOL} = m_{ref} * leak_{ref_{EOL}} * CO_{2eq\_ref} \quad (10)$$

The indirect emissions (Eq 11) are the emissions related to the energy (electric) consumption of the system during the MOL (Eq 12) where $\sum E$ is the yearly energy consumption of the whole refrigeration system and CO_{2eq_elec} is the GWP for the production of 1kWh of electricity, depending on the electricity mix of the country.

$$\sum IEm = IEm_{sys,MOL} +/- IEm_{cluster} \quad (11)$$

$$IEm_{sys,MOL} = n * \sum E * CO_{2eq\_elec} \quad (12)$$

The embodied emissions (Eq 13) are the emissions related to the manufacture called Beginning of Life (BOL) (Eq 14 and 15) and EOL treatment (Eq 16), where m_{mat} is the mass of material substance in each technical components, except the refrigerant, R is the percentage of refrigerant recycled at the EOL, E_{recycl_mat} is the electric consumption for recycling the components, CO_{2eq_X} is the GWP for the manufacture of the components (CO_{2eq_manuf}), of the refrigerant (CO_{2eq_ref}), or EOL treatment ($CO_{2eq\_recycling}$), including refrigerant EOL. The data related to the EOL treatment of the refrigerant have been taken from Cascini et al.

(2013).

$$\sum EEm = EEm_{sys,BOL} + EEm_{ref,BOL} + EEm_{sys,EOL} +/- EEm_{cluster} \quad (13)$$

$$EEm_{sys,BOL} = \sum m_{mat} * CO_{2eq\_manuf} \quad (14)$$

$$EEm_{ref,BOL} = m_{ref} * (1 + n * leak_{ref_{year}} - R)\, CO_{2eq\_ref} \quad (15)$$

$$EEm_{sys,EOL} = \sum E_{recycl\_mat} * m_{mat} * CO_{2eq\_recycling} \quad (16)$$

The lifetime of the refrigeration system n is considered to be ten years.

The necessary properties (GWP of each material manufacture, electricity) were found in EcoInvent v3.8 database (Wernet *et al.*, 2016).

2.3.3. Total cost

To evaluate the cost of the refrigeration system through its lifecycle, the chosen metric is the Total Cost of Ownership (TCO) (Ellram 1995). It is calculated as the addition of all the direct and indirect costs during the system lifecycle, as illustrated by Figure 4. It consists in the sum of the capital costs (CAPEX) and the operational costs (OPEX).

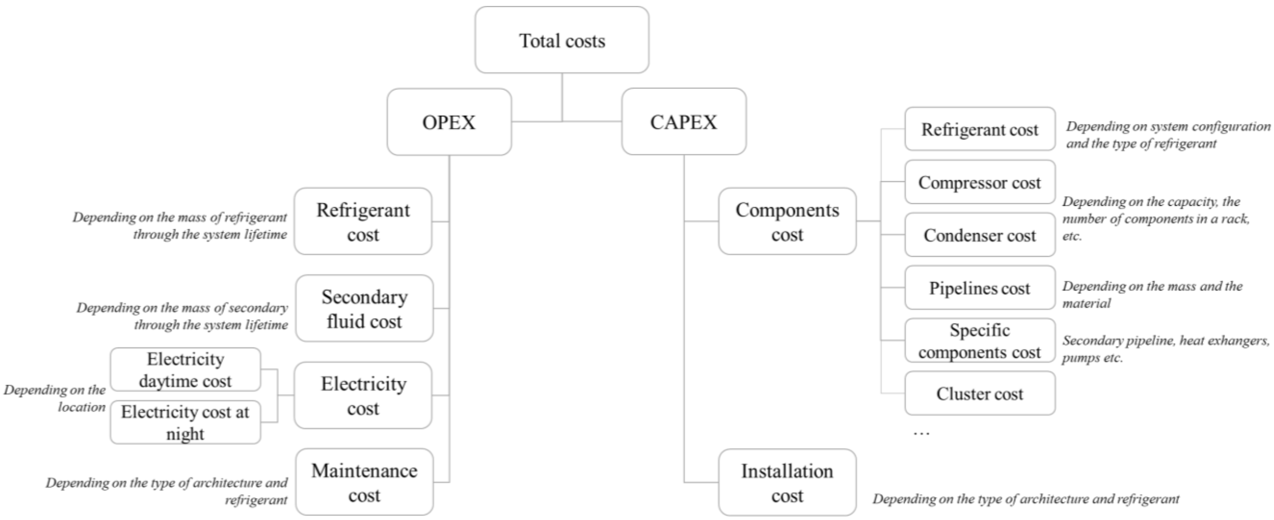


Figure 4. Calculation of the TCO metric

The TCO is calculated based on the following equations:

$$TCO = CAPEX + OPEX \quad (17)$$

Where

$$CAPEX = \sum C_{comp} + C_{inst} \quad (18)$$

And

$$OPEX = C_{ref,MOL} + C_{elec,MOL} * n + C_{maint} \quad (19)$$

where C_{comp} are the purchase costs of the components, including the purchase cost of the refrigerant at the BOL, C_{inst} are the installation costs depending on the type of architecture, $C_{ref,\text{MOL}}$ is the cost of refrigerant throughout the exploitation phase, $C_{elec,MOL}$ is the yearly cost of electricity depending on the system consumption, C_{maint} is the maintenance cost throughout the system lifecycle depending on the type of architecture.

The installation costs depend on the cooling requirement in kW and the type of architecture installed as shown in Table 3. The maintenance costs depend on the system architecture. Indeed, regulations recommend or impose one maintenance operation per year for DX system using certain fluids, while CO_2 systems can have one operation every two years (EN 378, 2017). The installation and maintenance costs (from installation companies), consistent with some insights found in the ICF consulting report (2005), are shown in Table 3.

Table 3. Installation and maintenance costs depending on architecture type

Type of architecture	DX	PI	SL	TR
Installation cost (€/kW of cooling requirement)	60	60	80	100
Maintenance costs (€/kW of cooling requirement/year)	60	60	30	40

2.3.4. Maintenance score

Refrigeration system maintenance is an important part of the exploitation phase in the life cycle. It ensures the efficiency of the machines and avoids breakdowns and accidents. The maintenance activities are standardized, i.e. should respect guidelines (number per year, certifications for operators according to the refrigerant, procedures, reports, etc.).

The latest studies on maintenance assessment for refrigeration systems or building highlights that the most widespread and easy quantitative method to assess maintenance is by cost analysis. For example, Alrwashdeh and Ammari (2019) establish a life cycle cost analysis, including in their model costs of acquisition, energy, repair, maintenance and disposal for two types of refrigeration system. Amrina *et al.* (2020) identify sixteen key performance indicators to measure sustainable maintenance in the cement industry. They include economic performances, such as maintenance cost or failure rate, social aspect such as training or employee involvement and environemental aspects with emissions or energy/material consumption. In the present paper, this maintenance cost is already included in the TCO assessment.

However, it is not simple to qualitatively evaluated maintenance, due to the complexity of the systems, the organizations involved, the technologies and the standards that govern it (Amrina et al., 2020). By extending the field of research to ergonomics, another way to assess maintenance based on a qualitative approach can be considered. In this paper, the maintenance is evaluated both quantitatively by the TCO and qualitatively as a score that depends on the architecture and the refrigerant. It is based on four sub-classes from Geng *et al.* (2013): accessibility, error proofing, ergonomic and physical injury. Some evaluation elements, such as ergonomics is adapted for refrigeration systems, as well as rank illustrations.

The maintenance score is evaluated as follows:

$$Maintenance\ score = Architecture\ score + Refrigerant\ score + Cluster\ score \qquad (20)$$

Where

$$Architecture\ score = accessibility\ score + \ error\ proofing\ score + \ ergonomic\ score + \ physical\ injury\ score \qquad (21)$$

$$Refrigerant\ score = \ error\ proofing\ score + \ physical\ injury\ score \qquad (22)$$

And $Cluster\ score$ is the score of a potential technological cluster.

The scores are calculated according to Table 4. The illustrations in columns A, B and C correspond to a score of 0, 2 and 4 respectively. The higher the score, the more difficult the system is to be maintained and installed.

Table 4. Maintenance qualitative assessment table adapted from (Geng et al. 2013)

EVALUATION ELEMENT		**ILLUSTRATION OF RANK A**	**ILLUSTRATION OF RANK B**	**ILLUSTRATION OF RANK C**
Accessibility	Visibility	System could be seen directly	Target could be seen partly	Target could not be seen at all
	Reachability	The system could be reached easily	The system could not be reached easily	The system is not reachable - risk of approaching instinctively
	Operation space	Maintenance staff could operate freely	Maintenance staff collides with surroundings sometimes	Maintenance staff always collides with surroundings
Error proofing	Error proofing	Safety accident could be reduced effectively	Safety accident could be reduced to a certain extent	Safety accident may happen probably by inexperienced staff
	Marking	Distinct and logical marking	Confused and fragmentary marking	Few marking design could be found
Ergonomic		Acceptable ergonomic design	Ergonomic design need to be rapidly investigated further	Ergonomic design need to be investigated further and change immediately
Physical hurt preventing	Heat/ Electrical/ Mechanical injury preventing	Adequate protecting devise is set, no contact between human limb and dangerous surface	Protecting devise is deficient or human limb is in contact with dangerous surface sometimes	Few protecting devise could be discovered or human limb is always in contact with dangerous surface
		Electric power is shut down in simulation and corresponding electricity cables wire away from sharp edge	Live working is avoided but electricity cables contact with sharp edge in several conditions	Live working is not avoided no matter electricity cables wire probably or not
		Sharp edge is precisely chamfered	Chamfer is missing in some positions	Few chamfer occurred
SCORE		0	2	4

3. Results and discussion

In this section, three sets of results are presented. First, the model is validated by comparison with experimental data. Then, overall results in three European countries are presented and discussed. Finally, the model is applied to study two scenarios: (i) the addition of a technological cluster (photovoltaic panels); (ii) the influence of economic support for installing more sustainable refrigeration systems.

3.1. Model validation

To check if the modelling method is well implemented, the *energy consumption* of a refrigeration system only for food storage was simulated and compared to experimental data taken from a case study of supermarket (ADEME and Enertech 2001). These experimental data of energy consumption are collected thanks to different sets of sensors. As the data reported date from 2001, the refrigerant regulation from 2001 was applied, thus using R134 and 404 as refrigerants. The other technological components are adapted from the platform modelled alternatives .

The supermarket is composed of 25 display cabinets (DC) with a positive set-point temperature at 2°C, 8 DC and 1 cold room with respective negative set-point temperature of -18°C and -20°C. The DC can be vertical or horizontal with a respective mass of food of 50 kg and 30 kg. To simplify the modelling validation, the models consider that the food at positive temperature is fruits in bulk and ice cream at negative temperature. The total energy consumption only for refrigerated or frozen food storage for a whole year measured in the report is around 291,600 kWh.

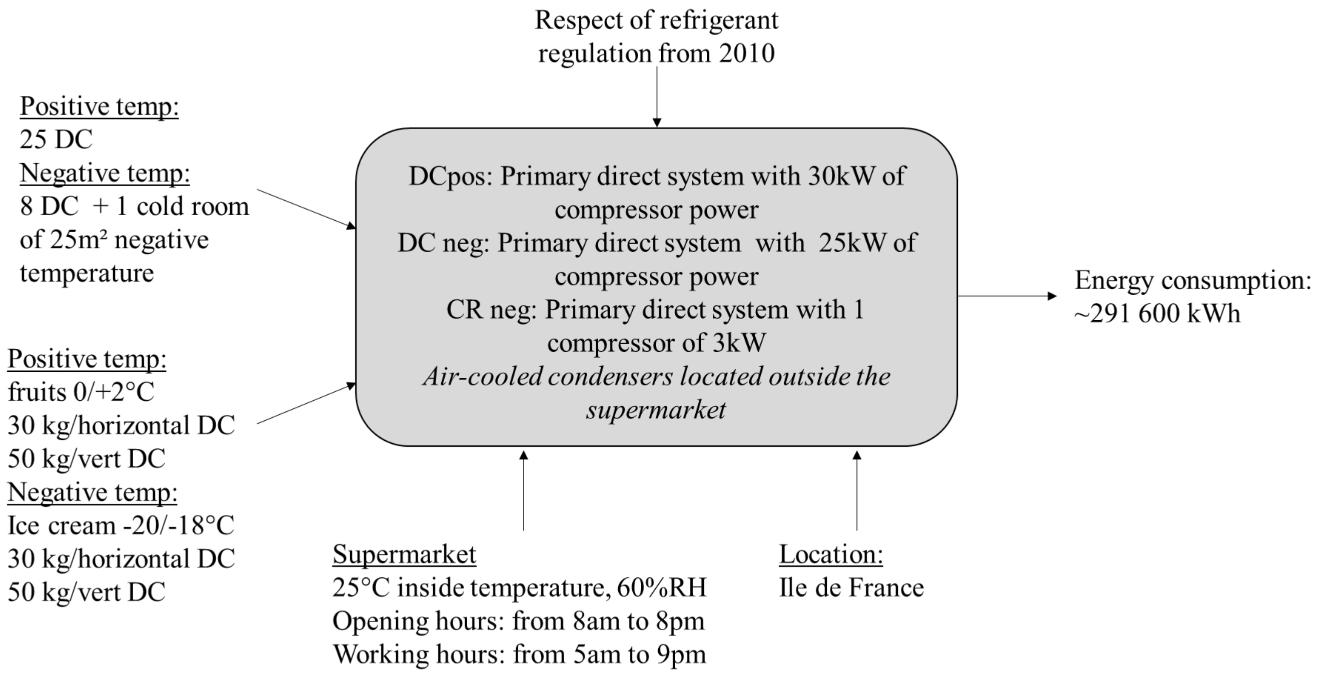


Figure 5. Reference supermarket for verification of the models

The system structure should be the same or as close as possible to the real system in place. The system architectures for both temperature and the three types of refrigerated storage (horizontal, vertical DC and cold room) are primary direct expansion architecture. As the type of compressors was not specified in the report, the choice of compressors was made based on the cooling requirement and the type of refrigerant.

The yearly reported data from the ADEME case study is 291.6 MWh only for food storage. Moreover, the daily energy consumption provided in the ADEME report is 400 kWh/day in winter and 740 kWh/day in summer. These data are probably averaged values but corresponding weather temperature profiles are not provided in the report. In addition, temperature data from 2001 are not available, only extreme temperature can be found: for instance in Paris varying between -1 °C in December and 36 °C in July. However, to verify our model, it is necessary to consider annual weather temperature profiles. Consequently, weather data from 2018 were chosen in the model, with average values varying over the year between 2.7 °C and 25.2 °C. Nevertheless, the technological components of the refrigeration system used in the model correspond to those of the ADEME report. Finally, calculated data corresponding to 2018 vary between 500kWh/day during winter and 770 kWh/day during summer. The yearly consumption calculated with the model is 252.7 MWh. It is lower than the reference case study of 291.6 MWh by 12 %, which is acceptable considering that different factors impact the result. The difference in monthly consumption can be explained mainly by the weather data taken into account in the model and that of 2001.

Other factors highlighted by stakeholders can explain the difference:

- The simplification hypothesis for the mass and type of food, type of cold room and display cabinets or the choice of components;
- The technological modules in the model are newly developed technologies and their energy consumption has been well optimized in the last decade;
- The general hypotheses on the supermarket specifications (number of employees, opening hours, constant temperature in the store, the humidity level, etc.)
- The simplified parameters for the evaporator and heat exchanger dimensioning.

Considering these various factors, the comparison of the energy consumption between the simulation and the experimental data shows a good agreement. These results were also presented to several professionals from an installation company for verification. These professionals confirmed that the 12% difference was acceptable.

It is necessary to emphasize that the accuracy of the present model was verified by calculating a single overall performance: the energy consumption. Meanwhile, the environmental impact is generally used to compare different architectures and was evaluated in the following section. Moreover, the cost performances and maintenance scores attributed to the different architectures and components were discussed and the assumptions made were verified through interviews with a group of industrial experts (French companies designing and installing refrigeration systems).

3.2. General computation results

In this section, the model results are obtained for a typical supermarket in three locations: Paris, Stockholm and Toledo. Indeed, among the European countries, the objective is to test several climate zones: a "cold" climate, a "warm" climate and a temperate climate. For the "warm" climate, Toledo was chosen. Indeed, central Spain is considered one of the hottest regions in Europe, with summer temperatures reaching 40°C as in July 2022.

In the following, the results include the compressor power per month, the yearly energy consumption for food conservation at medium and low temperature, the lifecycle climate performance (LCCP), the total cost of ownership (TCO) and the maintenance scores. The detailed results can be found in Table 6.

3.2.1. Energy performance results

Figure 6 represents the yearly energy consumption for food preservation in supermarket for the three locations and the four studied architectures: centralized direct expansion using R404 (DX) in red, secondary loop using glycol water (SL) in green and CO_2 transcritical system (TR) in blue, plug-in (PI) using R290 in yellow striped.

The store and food conservation parameters such as supermarket internal temperature or food storage temperature are the similar for all three locations (Table 1), which explains why they have the same cooling requirement. However, the performances depend on the chosen architecture, associated components and weather. In particular, energy consumption differs depending on the location for the first three architectures (DX, SL, TR). Indeed, their condenser is located outside the supermarket and therefore depends on the outdoor temperature. The fourth architecture (PI) does not depend on the outdoor temperature, only on the supermarket internal temperature, but was included in the study for comparison.

For all three climate zones (Paris, Stockholm and Toledo), TR system is the most efficient, except PI in Toledo since it does not depend on outdoor temperature in the present simulation. This result is consistent with other studies (Sun et al., 2020), although TR system strongly depends on outdoor temperature as shown in Figure 7 representing the needed compressor power of the four architectures over the year. It should be remembered that the data used in this study comes from manufacturers (BITZER, 2017). According to these data, above a certain temperature (here 20 °C), CO_2 equipment goes into a "degraded" mode, which means that one or more back-up compressors using R134 are used to meet the cooling needs. TR systems are therefore able to overcome this difficulty (for now) while offering the best energy performances. Indeed, while the use of additional backup systems adds extra energy consumption (and by extension additional costs and environmental impacts), the system only operates in a degraded mode a few times a year. The results of energy consumption for TR systems are consistent with the results obtains in the literature. Indeed, Gullo et al. (2017) show that CO_2 systems can save between 2 and 20% of energy consumption compared to DX. Moreover the COP of TR varies between 3.1 during winter and 4 during summer in Spain. As pointed out by Azzolin et al. (2021), TR are highly subject to the variation of the outside temperature.

Depending on the climate zone, the highest consuming system can be one of the other three architectures. Indeed, in France and Sweden, SL and PI systems are the most energy-intensive, whereas in Spain, DX system is largely more energy-intensive than the others. The high electric consumption of SL system can be explained by the number of pumps and other components necessary to transport the secondary fluid to the display cabinets and cold rooms. However, this could be compensated by adding cold storage to the circuit or by testing other types of secondary fluids such as phase change fluids.

In Spain, the direct expansion system is significantly more energy intensive than in France or Sweden. Several factors can explain this observation. Firstly, the system is designed to meet greater needs than in France or Sweden. Indeed, the outside temperatures are on average higher than in France (+6°C) or Sweden (+10°C). In addition, a large amount of energy for the compressors is needed to meet the temperature variations to which DX is more sensitive.

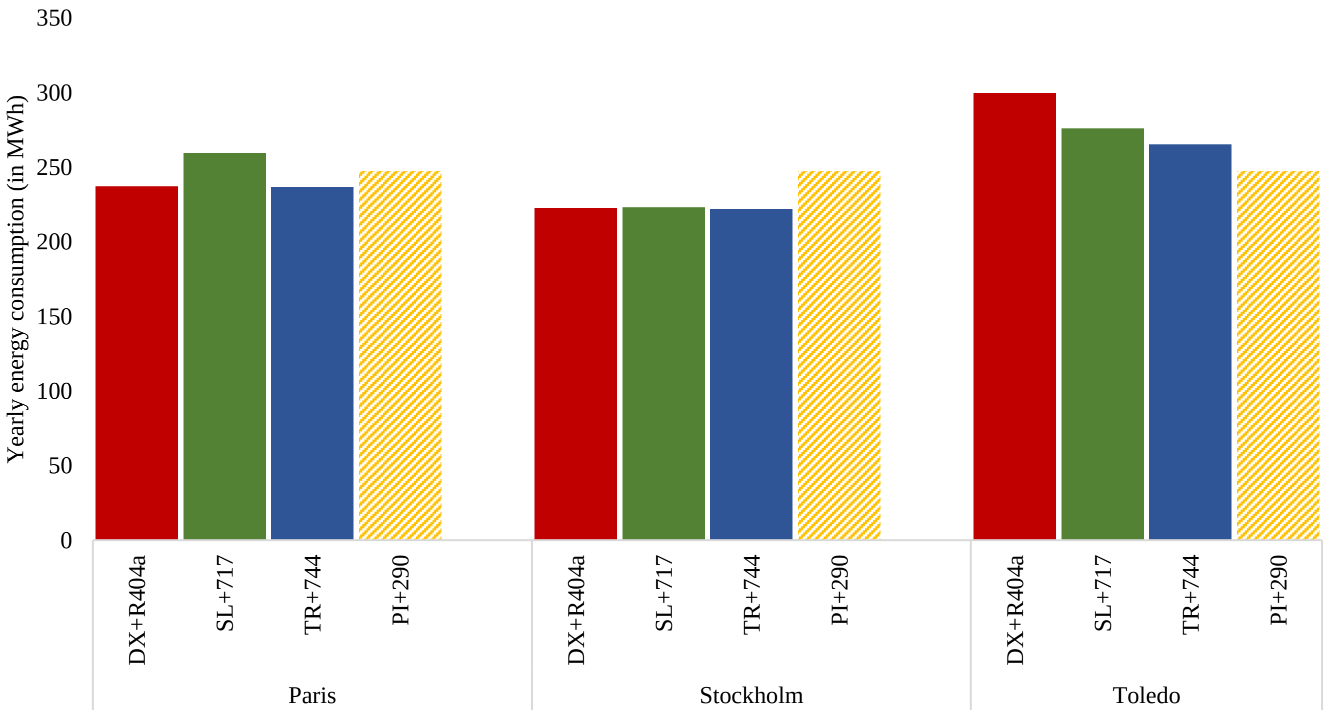


Figure 6. Yearly energy consumption for a supermarket in three locations with four architectures: DX; SL; TR; PI.

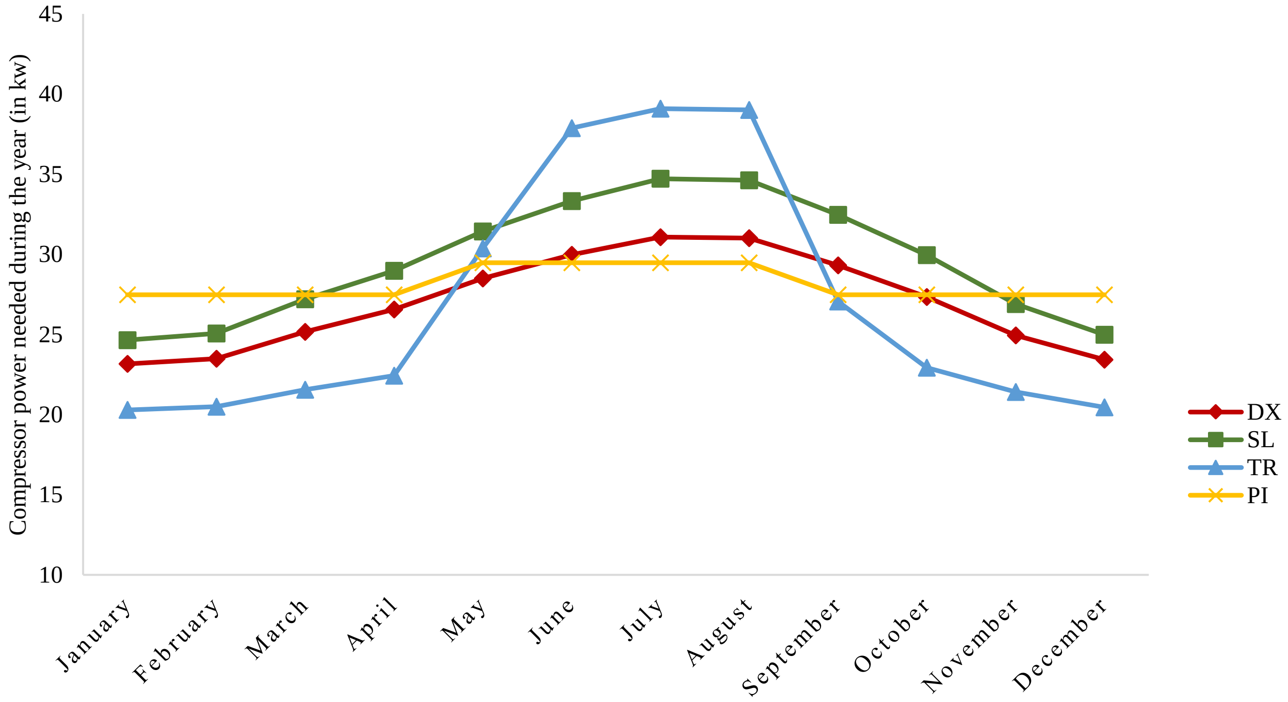


Figure 7. Needed compressor power depending on the month in Paris, France, calculated with 2018 data.

3.2.2. Environmental impact results

Figure 8 represents the LCCP calculated over ten years for the three locations and the four architectures. Above the histograms, the rings represent the electricity mix of each country expressed in $kgCO_2eq/kWh$. As Sweden mix is 60 % renewable energy, it has a low CO_2 emissions. France is also relatively carbon neutral with over 65 % nuclear. As Spain electricity mix is mostly composed of gas, coal and oil, the CO_2 emissions are high. According to many studies, the most impactful phase of a refrigeration system is the operation phase. This is why the electricity mix is an important factor in determining environmental impacts.

The second most important factor in environmental impacts calculation is the type of fluid and the leakage during the different life cycle phases. Indeed, the GWP in the use phase of R404 is 3920 kg $CO_{2\,eq}$ / kg of fluid. The environmental impact of its production is about 130 kg $CO_{2\,eq}$ / kg of fluid, according to EcoInvent v3.8 data. The GWP of R290 in the use phase is 3 kg $CO_{2\,eq}$ / kg of fluid and its production is about 0.51 kg $CO_{2\,eq}$ / kg of fluid. For R717 and R744, the GWP of production is higher that their usage GWP, respectively 0 and 1 kg $CO_{2\,eq}$ / kg of fluid. This explains why R404 systems can have a high environmental impact.

Circuits with a secondary loop are among the most impactful system. This can be explained by the higher number of components used than for PI or DX, the high power consumption and the use and leakage of R404 in the primary circuit.

Plug-in systems are the second most impactful system in France and the first in Sweden, due to its high power consumption and the production and end-of-life treatment related to noise and heat insulation (insulating foam) in such systems.

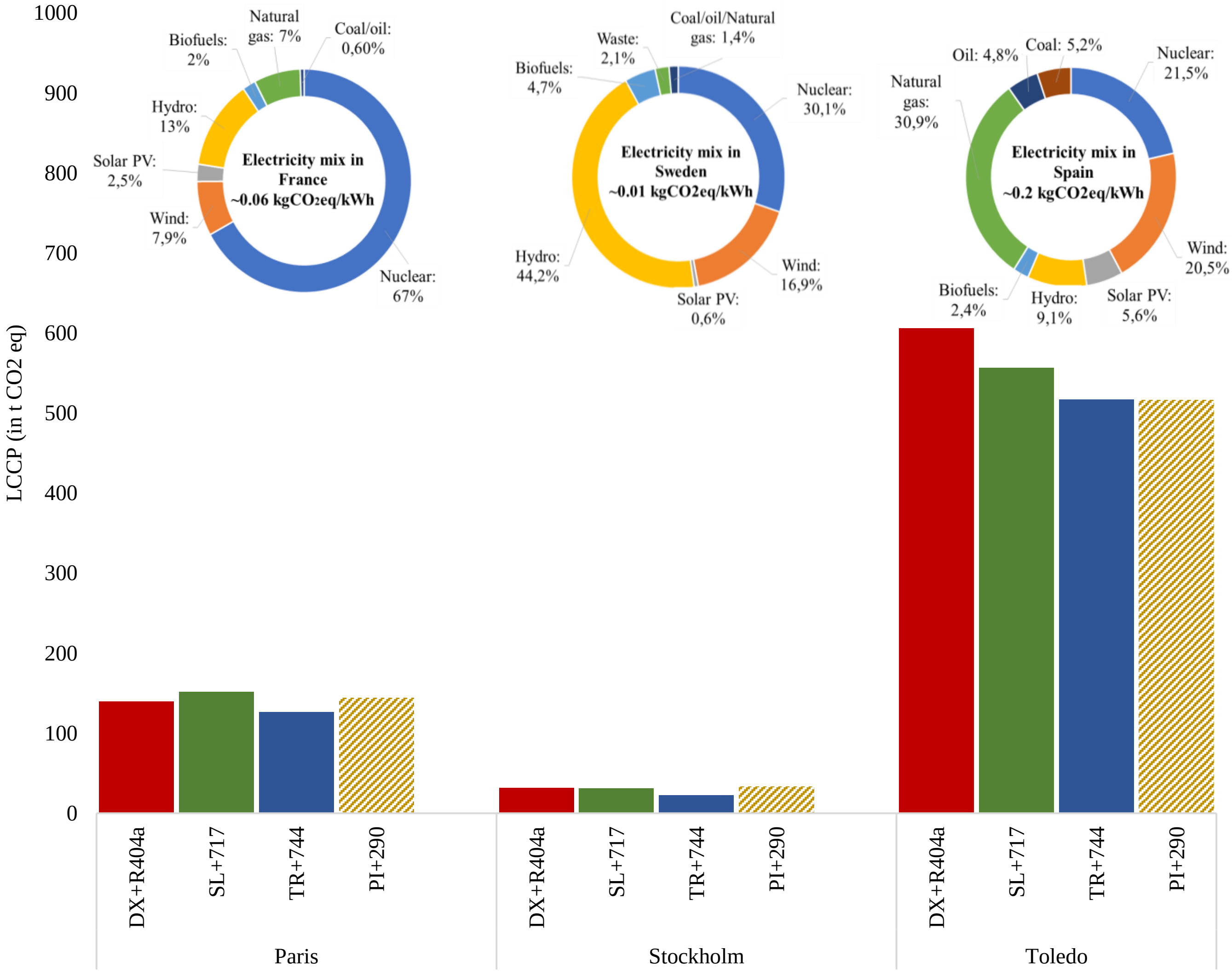


Figure 8. LCCP calculated over ten years in three locations with four architectures: DX; SL; TR; PI (data of electricity mix from Eurostat).

3.2.3. Total cost results

Figure 9 presents the comparison histogram of the average annual TCO calculated over ten years for the three locations and the four architectures. As a reminder, TCO is an economic approach to calculate the total costs of a system during its entire life cycle (from manufacture to end-of-life treatment). In this case, the calculation of TCO is presented in section 2 and equations (17) to (19). In Figure 10, it is calculated over the 10-year life of the system and then averaged over the year to facilitate interpretation. Above the histograms are the electricity mix of each country expressed in €/kWh obtained in the European database Eurostat. First, the TCO for all three locations are highly depending on the electric consumption of the systems and thus on electricity mix. This is why the TCO in Sweden is considerably lower than in Spain, where the kWh costs are twice as much.

In France and Sweden, plug-in systems are the most expensive. This can be explained by the assumption applied for the plug-in units. Indeed, the model considers that for the three countries, the units are purchased independently of the furniture. It is thus more expensive, while in real conditions the furniture and the PI unit are purchased together. Moreover, OPEX is the most impacting cost in the TCO calculation. PI requires higher operating costs than other systems. However, these costs could be amortised by reducing the costs of heating the supermarket in an overall HVAC model.

DX systems are also expensive. This can be explained by several factors. Firstly, the fluid R404 used in this study is about 4 to 10 times more expensive than R290 or R744. The mass of the fluid used in the system and the high leakage rate, 15-25% for DX versus 5-10% for SL, impact the TCO balance. Moreover, the DX installation costs are lower than those for SL and TR. However, the maintenance of DX must be done more regularly, at least once a year, compared to once every two years for SL or TR.

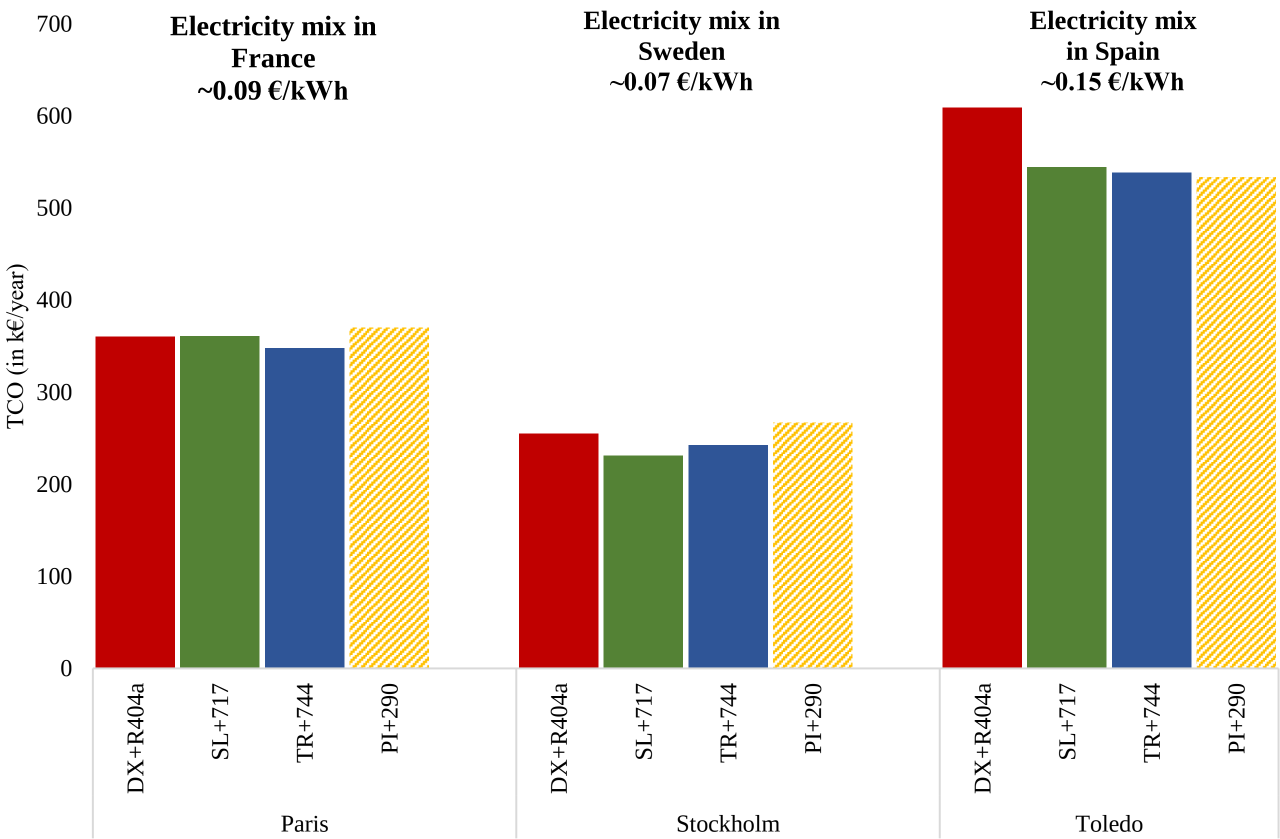


Figure 9. Average annual TCO calculated over ten years for a supermarket in three locations with four architectures: DX; SL; TR; PI (data of electricity mix from Eurostat).

3.2.4. Maintenance results

The maintenance score for each architecture and refrigerant is presented in Table 5. Maintenance was already taken into account quantitatively in TCO sections. In this section, the maintenance is assessed based on the qualitative analysis of the domain experts from French installation and maintenance companies. The architecture maintenance score is based on the installation, maintenance and EOL handling of the system.

DX or SL systems are the most frequently used system for supermarket due to their ease of installation, and better operator experience. However, the maintenance is more frequent because of R404a usage. Moreover, condensers located on the rooftop require a secured accessibility for the operators.

PI systems demand is extending in supermarkets as their use allows for greater flexibility in the floor layout. They are also less expensive and do not require difficult installation conditions. However, it is more complicated to maintain, because of limited accessibility to the components as the unit is embedded in the cabinet. In addition, R290 is flammable and hazardous to human health, which makes the PI score the highest.

TR systems are interesting for their lower energy consumption, costs and environmental impacts. However, the score of CO_2 system is high as the installation, maintenance and EOL treatment phase are still challenging. The use of CO_2 requires a particular organization of the space for their installation. Indeed, more space than for other architectures is needed and specific markings for pressure equipment must be present. CO_2 maintenance requires staff certification renewed every 5 years. Moreover, despite less frequent maintenance during the usage phase than for systems using R404a or R290, hot temperature in the summer could cause more frequent stop in the machine. Finally, the EOL treatment parties are not yet prepared for such system (Salehy *et al.,* 2021).

Due to lack of knowledge for each component of the system, the score is assessed only depending on the architecture and refrigerant used. It should be completed with the scores of each component, for example type of installed compressor or condenser.

Table 5. Maintenance score for each architecture and refrigerant

Category	DX	PI	SL	TR
Ergonomic	2	4	2	2
Error proofing	2	0	2	4
Marking	2	0	2	2
Operation space	0	4	0	0
Reachability	2	4	2	2
Visibility	2	2	0	0
Architecture maintenance score	*10*	*14*	*8*	*10*
	R404a	R290	R717	R744
Error proofing	2	2	2	4
Marking	0	2	2	2
Physical hurt preventing	0	4	2	4
Refrigerant score	*2*	*6*	*6*	*12*
Total maintenance score	**14**	**22**	**14**	**20**

Table 6. Detailed results of the performances (mean compressor power, total electric consumption per year, TCO and LCCP) for each location and architecture

	PARIS				STOCKHOLM				TOLEDO			
	DX	PI	SL	TR	DX	PI	SL	TR	DX	PI	SL	TR
Mean compressor power (kW)												
January (min)	23.2	27.5	24.7	20.3	19.5	27.5	18.5	21.3	28.7	27.5	25.6	24.9
July (max)	31.1	29.5	34.7	39.1	31.4	29.5	32.6	29.4	40.4	29.5	38.1	39.1
Total electric consumption per year (MWh)	**234**	**243**	**255**	**232**	**219**	**243**	**219**	**218**	**295**	**243**	**271**	**261**
(€)												
CAPEX	60,835	50,550	62,959	62,210	60,898	50,550	62,590	60,554	62,436	50,550	63,535	62,205
OPEX	326,996	346,708	396,115	394,784	246,862	340,372	268,908	291,685	535,905	456,925	522,326	530,109
TCO divided by the system lifetime	**387,831**	**397,258**	**459,074**	**456,994**	**307,760**	**390,922**	**331,498**	**352,239**	**598,342**	**507,475**	**585,860**	**592,314**
(kg CO_{2eq})												
$Em_{sys,MOL}$	137,615	143,455	150,512	137,193	30,404	32,996	30,462	30,318	601,331	513,639	553,283	531,908
$Em_{ref,X}$	14,430	54	4687	4,666	14,430	54	4,687	4,666	14,430	54	4,687	4,666
LCCP divided by the system lifetime	**159,648**	**150,684**	**162,958**	**148,952**	**47,075**	**34,703**	**36,907**	**36,734**	**646,549**	**539,377**	**585,868**	**544,642**

3.3. Scenario comparison

In this section, the model is applied to two scenarios:

(1) Photovoltaic (PV) panels are installed on the supermarket roof. In this scenario, the aim is to analyse the PV panel impact on the refrigeration system performances. The detailed results can be found in Table 8.

(2) A financial support is proposed to the supermarket to help installing more sustainable refrigeration system. In this simple scenario, the aim is to discuss the impact of financial support on the possible installation of a new system.

3.3.1. Scenario 1: Photovoltaic panel

To analyse this first scenario, several changes are necessary. The PV panels are defined in the conceptual design section (cf. 2.2) as a new technology cluster that is added to the system structure. The terms contributing to the general equations should then be added in the embodiment design phase (cf. 2.3). The modifications are established as follows:

1) Firstly, the energy provided by the PV panels has to be subtracted in the overall calculation of energy consumption (Eq. 3). The term $E_{cluster}$ is then used to calculate the contribution of the PVs:

$$E_{cluster} = -E_{PV} \tag{23}$$

The daily energy intake of PV panels depends on their type, maximum power, temperature, surface of panels installed, solar radiation and outside temperature:

$$E_{PV} = PR * A_{PV} * P * SR * r \tag{24}$$

With PR performance ratio, i.e. installation quality, considered to be 0.75; A_{PV} PV area in m²; P electrical power of one square meter in kWp/m²; SR the solar radiation in hours; r panel efficiency.

2) Then, LCCP is recalculated based on the energy gained with PV panels, the emissions due to the production and end of life of PV panels (from Eq. 7):

$$DEm_{cluster} = 0 \tag{25}$$

$$IEm_{cluster} = Em_{sys,MOL} \tag{26}$$

$$EEm_{cluster} = A_{PV} * CO_{2eq\_PVmanuf} \tag{27}$$

With A_{PV} area of panels installed and $CO_{2eq\_PVmanuf}$ GWP of panels manufacture in kg CO_{2eq}/m².

3) Third, TCO is calculated based on the energy consumption, PV panels installation and maintenance costs. It should be noted that maintenance in the presence of PV is annual: for example, in the case of

TR system without PV, maintenance is performed every two years, while with PV, maintenance is annual.

4) Finally, the operational maintenance score related to the PV panels score is added to the general score.

Figure 10 represents average annual TCO vs. average annual LCCP calculated over ten years for all three locations and the four architectures, without (full points) and with (empty points) PV panels. As expected, the higher the environmental impact of the electricity mix and the higher the cost of a kWh of electricity, the more points are located in the area to the right and at the top of Figure 10 as is the case for Toledo before the use of PV.

For Stockholm and Paris, the impact of PV is not as obvious as for Toledo. This can be explained by the electricity mix and local climate in Sweden and France. However, in Toledo, the contribution of PV is multifold: from an economic point of view as well as on the global warming factor with a gain of almost 50 % regardless of the architecture. The results show that Toledo can become as economically interesting as Paris or Stockholm (only without PV). Consequently, Toledo results with PV can be close to the results of Paris or Stockholm (without PV).

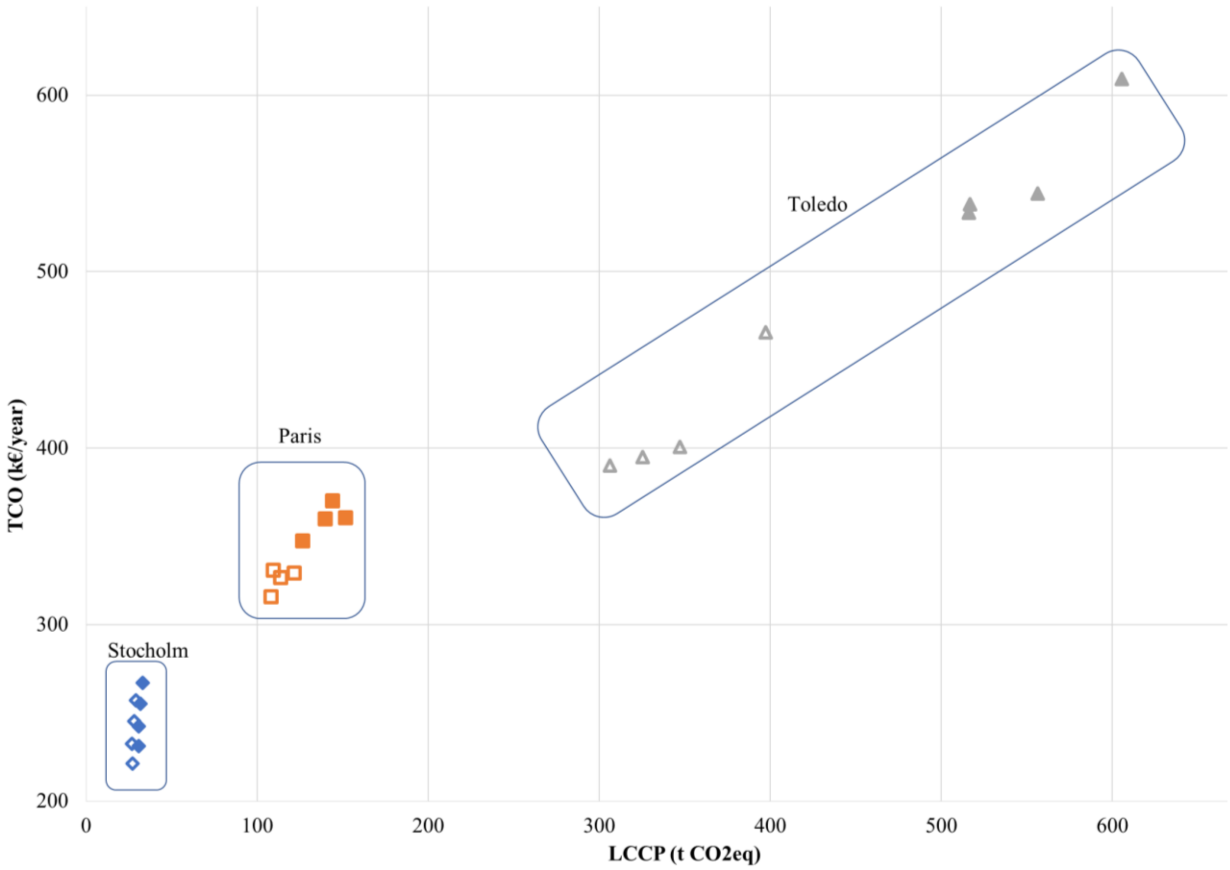


Figure 10. Average annual TCO/LCCP calculated over ten years for each architecture (DX, SL, TR, PI) in Paris, Stockholm and Toledo without using PV panels (full points) and with using PV panels (empty points)

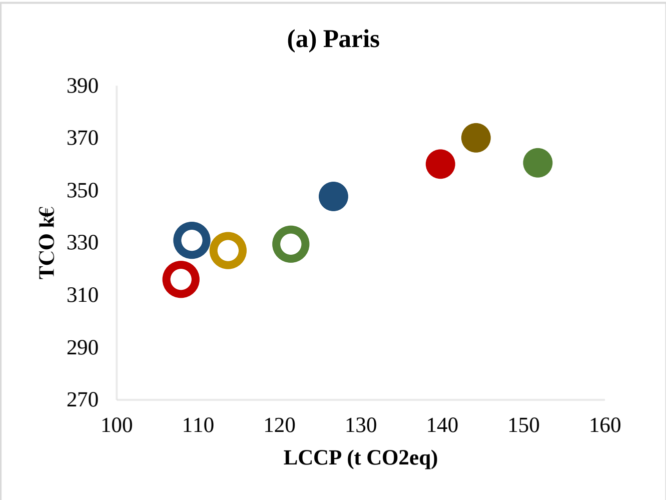
To go into more detail, Figure 11 shows the same comparison of TCO/LCCP points as Figure 10 at the scale of each location.

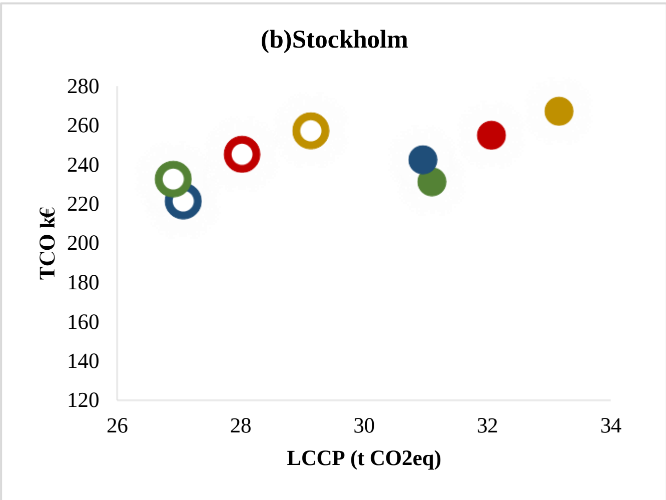
As said previously, the electricity mix of Sweden and France are more "neutral" than Spain's. In Sweden, the difference in LCCP is not significant with only a few tons of CO_{2eq} gained. Indeed, the mix is more than 60% renewable energy. In Paris, the difference in LCCP varies between 20 and 40 tons saved with the use of PV. In Spain, the difference is significant because the PV share covers more than half of the electricity consumption used, corresponding to a gain of more than 200 t CO_{2eq} per year.

The TCO reported at one year shows some differences with and without PV. The payback is different for the three countries. Indeed, in Spain where the cost of electricity is high, the considerable investment of adding PV panels is still paid back after 5 years. In France, the payback on PV is 7 years. However, in Sweden, the payback only comes after 9 years. In some cases, it is even more interesting to invest in certain new refrigeration system architectures than in installing PV. For example, installing SL (green in the figure) could be less expensive than installing PV with DX (red).

Besides, there is a gain of 10 k€ for Sweden, 50 k€ France and 150 k€ for Spain after 10 years. It could be even higher if the excess energy produced by panels is returned to the grid.

Finally, the use of panels does not clearly change the relative ranking of the architectures, in particular in Stockholm and Toledo. In Paris, however, there are some modifications of the architecture ranking with and without PV: SL presents the lowest (best) scores without PV, while DX have the best performances with PV.





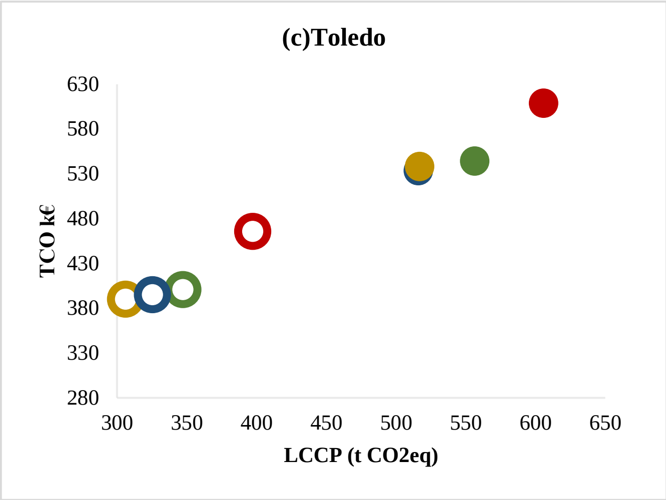


Figure 11. Average annual TCO/LCCP calculated over ten years without (full circles) and with PV panels (empty circles) for each architecture: DX (red), PI (yellow), SL (green) and TR (blue): (a) Paris, (b) Stockholm and (c) Toledo.

To better understand the main contributions in the results presented in Figure 10 and 11, the following two figures detail the TCO and LCCP performance for each architecture and location. Figure 12 represents TCO decomposed according to the three contributions (CAPEX, OPEX, Maintenance), in the first year of installation of the PV panels. It can be seen from the histograms that PV panels do not modify the order of the architectures. Nevertheless, the comparison of CAPEX, OPEX, especially Maintenance, is consistent with the result in Figure 11a regarding the reversal of the 10-year average trend between the DX and TR system with and without PV panels. Indeed, the TR maintenance with PV is twice as frequent (annual) as without PV. It leads to a significant increase in costs. Furthermore, the CAPEX for all countries is significantly higher due to the purchase and installation of the PV panels: about 500 € extra per square meters of installed panels. Due to the lesser availability of Sweden and Spain data, the PV cost data is considered the same for all three countries. However, the calculations give a realistic idea of the panels impact on the total cost.

In Spain, the panels installation allows a significant gain on OPEX from the first year. Indeed, the higher price per kWh in Spain depends partly on the price of natural gas, coal, oil and nuclear, themselves depending on possible economic crises. The addition of PV panels on the roofs allows energy autonomy for the supermarket and PV panels' return on investment is visible from the first year.

In France, the panels installation is also interesting from the first year, even if the difference is not significant. From the second year until the end of the system's life, the PV panels installation saves even more on energy consumption costs. In Sweden, as the electricity mix is already environmentally interesting, there is no obvious difference. Still, energy costs are reduced by almost a third in the second year. Moreover, it could be interesting to analyse additional energy return to the grid.

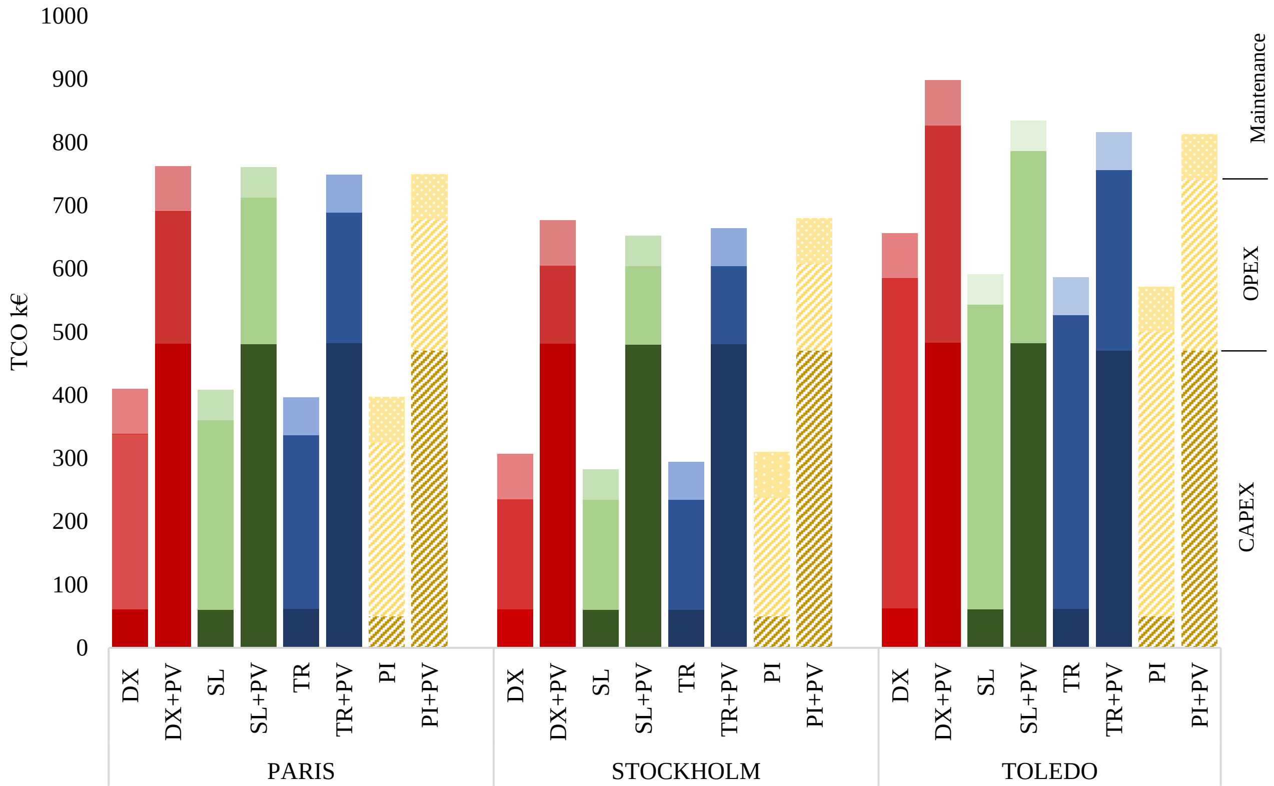


Figure 12. Total cost in the first year for the three locations and the four architectures (DX, SL, TR, PI) with and without PV.

Figure 13 shows CO_2 emissions based on LCCP calculation in the first year to show the global impact of PV production and use. The panels production is shown in grey on the histograms. In France and Sweden, the additional emissions due to PV production are significant, due to the electricity mix relatively neutral for both countries. However, over 10 years (not represented in Figure 13), the production impact is offset by the reduction of indirect emissions (Electricity emissions in Figure 13). On the contrary, in Spain, the additional emissions due to PV production is less significant compared to the global emissions, because the electricity mix is very impactful, and thus the panels production is quickly offset in the first year by reducing indirect emissions.

By adding PV panels to the system, the maintenance score changes. Indeed, the score increases by 12 points with the addition of a new cluster as presented in Table 7. As PV is located on the roof, the accessibility and ergonomic scores are impacted. However, the cluster score of 12 is the same regardless of the system architecture. Thus, the trend order does not change by adding PV panels when only taking into account the maintenance score.

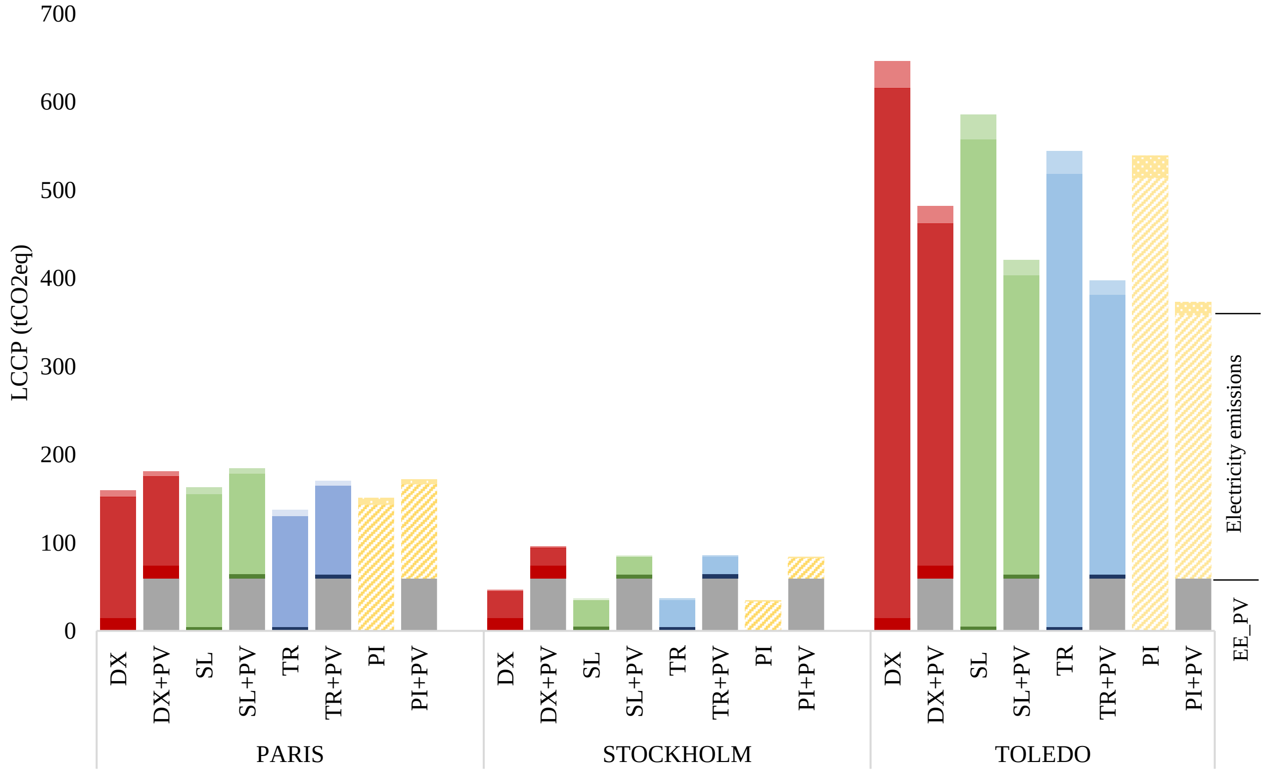


Figure 13. CO_2 emissions based on LCCP approach in the first year for the three locations and the four architectures (DX, SL, TR, PI) with and without PV (grey)

Table 7. Cluster (PV panels) maintenance score

Category	Score			
Ergonomic	*4*			
Error proofing	*2*			
Operation space	*2*			
Reachability	*2*			
Visibility	*2*			
Cluster maintenance score	**12**			
	DX+PV	PI+PV	SL+PV	TR+PV
New maintenance score	**26**	**34**	**26**	**32**

Table 8. Detailed results of the performances (Energy generated by PV panels, TCO, LCCP and cluster maintenance score) for each location and architecture

	PARIS				STOCKHOLM				TOLEDO			
	DX+PV	PI+PV	SL+PV	TR+PV	DX+PV	PI+PV	SL+PV	TR+PV	DX+PV	PI+PV	SL+PV	TR+PV
(MWh)												
Energy generated by PV	*66*				*76*				*109*			
Energy from grid	**168**	**178**	**190**	**167**	**143**	**168**	**144**	**143**	**185**	**134**	**162**	**152**
(€)												
CAPEX	480,834	470,550	480,558	482,209	480,897	470,550	480,190	480,553	482,436	470,550	482,436	470,550
OPEX	209,861	206,870	232,335	206,758	124,049	137,210	124,370	123,579	344,377	269,957	303,682	285,630
TCO divided by the system lifetime	**342,695**	**329,420**	**340,894**	**328,968**	**256,947**	**259,760**	**232,560**	**244,133**	**478,813**	**392,507**	**412,816**	**407,835**
(kg CO_{2eq})												
$EEm_{cluster}$	59,500	59,500	59,500	59,500	59,500	59,500	59,500	59,500	59,500	59,500	59,500	59,500
$IEm_{sys,MOL}$	101,298	107,203	114,425	100,975	20,463	23,076	20,526	20,369	388,052	298,748	339,218	317,556
LCCP divided by the system lifetime	**109,270**	**113,695**	**121,440**	**107,920**	**28,030**	**29,147**	**27,071**	**26,911**	**397,458**	**306,198**	**347,356**	**325,584**

3.3.2. *Scenario 2: Financial support*

In this second scenario, a financial support is proposed to the supermarkets to help toward the installation of new sustainable refrigeration systems. For halving energy consumption in France and encouraging companies to invest in more innovative systems, financial supports such as Prime CEE (Certificats d'Économie d'Énergie in French) are available. The French support base (*Loi n°2005-781*) is used to establish the calculations of financial installation support in the three countries. The systems considered eligible for this support in commercial refrigeration are SL and TR systems, as they can reduce drastically the amount of high-GWP primary refrigerant. For SL and TR studied in this work, the financial support is about 50 % and 30 % of CAPEX, respectively.

Figure 14 shows a comparison of the CAPEX and total costs the first year without and with financial support for the three locations and the four architectures. SL and TR systems CAPEX are often more expensive. Indeed, more specific components are needed, requiring a higher investment. With the financial support, TR and SL installation TCO is greatly reduced, which reverses the overall TCO. For example, SL becomes a competitive system whereas it was one of the most expensive systems. This kind of result can be useful for industrials who often find it difficult to invest more in innovative systems despite relatively similar or lower OPEX than direct or plug-in systems.

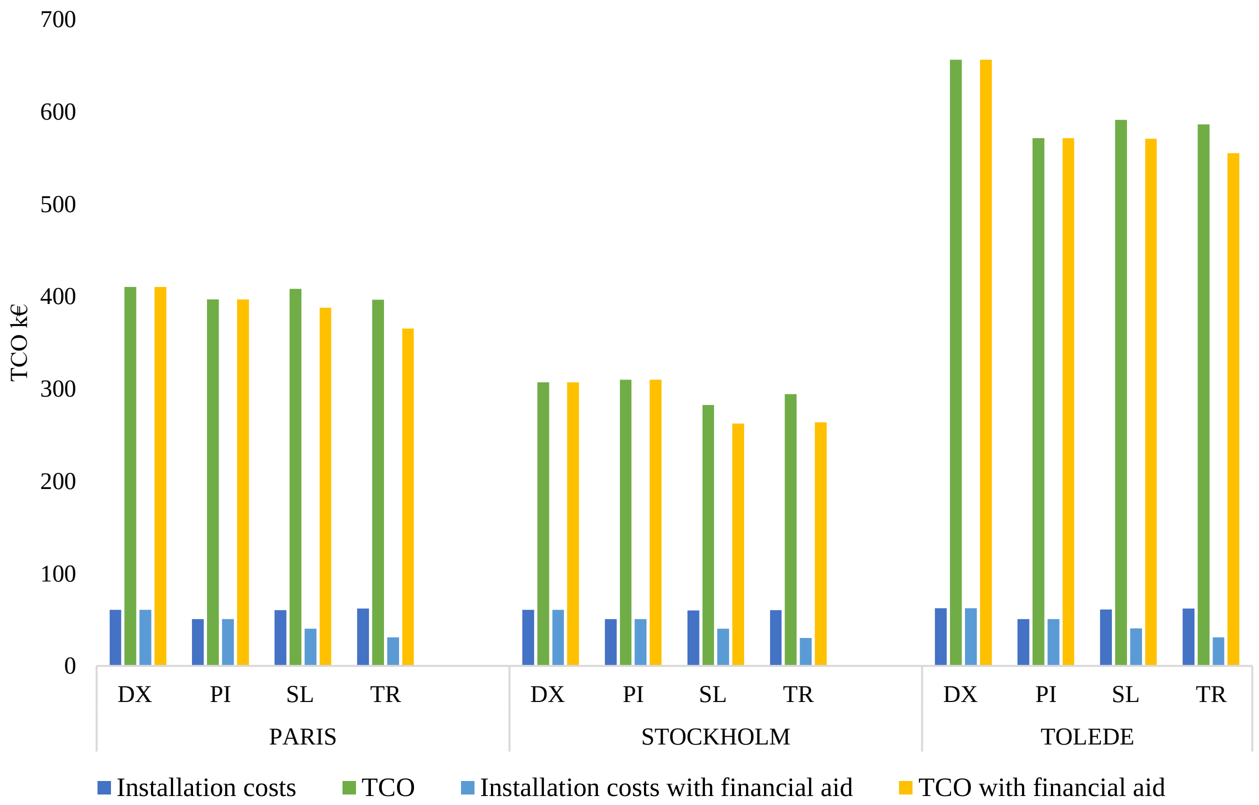


Figure 14. TCO comparison of CAPEX and total costs the first year without (dark blue and green histograms) and with financial support (light blue and yellow histograms) for eligible systems.

4. Conclusion

This paper proposes a multi-disciplinary (process engineering, industrial engineering) modelling of refrigeration systems. Three main modelling steps are defined for multi-performance analysis: task clarification with system environment modelling; conceptual design with solution/architecture definition; and embodiment design with performances assessment.

This work sets up a methodological structure to test different scenarios towards more sustainable systems. For this purpose, four performances are defined according to the pillars of sustainability: energy consumption, environmental impact through Life Cycle Climate Performance (LCCP), economic through Total Cost of Ownership (TCO) and social through maintenance scores. Although the maintenance score and TCO have a high level of uncertainty and should be discussed carefully, they are given as an indication toward the development of innovative technological cluster.

In this study, architectures and components already developed industrially are used to test the proposed approach. Main outcomes of this work are listed below.

- The proposed methodology allows the three pillars of sustainable development to be linked in a single analysis for refrigeration systems based on classical process engineering approaches and structured by industrial engineering knowledge. The feasibility of the proposed approach has been demonstrated. It would allow to test different innovative technologies in refrigeration to analyse their performance in real industrial cases or to highlight scientific or technical levers to their industrial maturity.
- The overall results show that the electricity mix (electricity cost, environmental impacts) is the most influential parameter on TCO and LCCP.
- The results show the interest of evaluating several performances within the same study. For example, the CO_2 transcritical system is interesting in terms of energy, environment and economy, but it is complicated to implement in a supermarket, which is an obstacle for industrials.

Two scenarios are analysed: use of photovoltaic panels; financial support for eligible systems.

- PV panels use is interesting for TCO and LCCP performances, but the TCO trend can be inversed because of frequency of maintenance. After 10 years, the installation of PV panels allows a good payback for the three countries: 10 k€ for Sweden, 50 k€ France and 150 k€ for Spain.
- Financial support can help the architectures with low direct impact (CO_2 transcritical, secondary loop) to be more competitive than those using large amounts of high-GWP refrigerant. It can reduce by 50% and 30% the installation costs for SL and TR respectively.

In further work, it would be interesting to test this methodology with technologies at low level of maturity, and to implement it in a design space exploration platform, i.e. a decision support platform in the early design phase for refrigeration systems. Different objectives could be explored. For example, studies are exploring the impact of undercrossing from an energy point of view and these models could be integrated into the proposed approach. Furthermore, it could be considered to focus on a specific life cycle phase of refrigeration system design such as end of life; or a particular technology such as those presented in the introduction.

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