# Life cycle assessment of hypermarket refrigeration system: effects of location and choice of architecture

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# ANALYSE DE CYCE DE VIE D'UN SYSTEME DE REFRIGERATION D'HYPERMARCHE : INFLUENCE DE LA LOCALISATION ET DE L'ARCHITECTURE DU SYSTEME

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Taking into consideration all the life cycle of a product is now an important step in the design of a product or a technology. Despite the improvement in refrigerant regulation, the environmental impacts of refrigeration systems remain important and need to be improved. In this paper, the environmental impacts of refrigeration systems in a typical hypermarket are compared using the LCA methodology under different conditions. The system is used to provide cold at two levels of temperature: medium and low temperature during a life period of 15 years. The most commonly used architectures of hypermarket cold production systems are investigated: centralized direct expansion systems and indirect systems using a secondary loop to transport the cold. The variation of power needed during seasonal changes and during the daily opening/closure periods of the hypermarket are considered. R134a as the primary refrigerant fluid and two types of secondary fluids are considered (liquid $CO_2$ and ammonia). The composition of each system and the leakage rate of the refrigerant through its life cycle are taken from the literature and industrial data. Twelve scenarios are examined. They are based on the variation of three parameters, 1. location: France (Paris), Spain (Toledo) and Sweden (Stockholm), 2. different sources of electric consumption: photovoltaic panels and low voltage electric network and 3. architecture: direct and indirect refrigeration systems.
SimaPro software was used to assess the environmental performances and different impact assessment methods were used; CML method is used to evaluate the midpoint environmental indicators and IMPACT 2002+ to assess endpoint indicators.
This study highlights the most environmentally damaging parameter to be electric consumption compared to the impacts of refrigerant leakage supporting the conclusions of previous studies. The use of a secondary loop lowers the refrigerant amount in the primary loop and thus the climate change indicator is reduced. The cost estimation of CAPEX and OPEX shows that depending on the location the use of photovoltaic panels can be more expensive and does not bring any improvement in environmental impacts.

**Keywords**
eco-design, Life-Cycle Assessment (LCA), refrigeration system, system architecture, cost estimation.

## INTRODUCTION

As the Earth population increases, the consumption of products and systems in every field is in constant growth. Cold production is needed in multiple domains such as food industry, pharmaceutical domains, buildings, supermarkets, transport… The importance of the refrigeration industry is expected to increase due to global warming and further growing of cooling needs. Thus, the role of the refrigeration industry in the global economy will be developing [1].

Thus the global cold production is regularly and significantly growing which leads to an increase in energy consumption. Nowadays, refrigeration is responsible for approximately 17% of the total electricity used worldwide and 3 to 5% of annual electricity consumption in North East Europe is used in supermarket applications [2]. In addition to the important electric consumption, refrigeration systems use refrigerant fluids which can be toxic for the environment or human health. Cold production systems are responsible for considerable $CO_2$ emissions in the atmosphere. To reduce direct and indirect effects related to the production, use and end-of-life of refrigeration systems, it becomes a necessity to assess the environmental impacts of existing and emerging technologies. Life cycle assessment (LCA) is a standardized tool [3] to evaluate the environmental impacts of a system or a process. Despite the improvement in refrigerant regulation through protocols and standards [4]–[7], the environmental impacts of refrigeration systems remain important and need to be improved.

In this paper, the environmental impacts of refrigeration systems in a typical hypermarket under different conditions are calculated using the LCA methodology and an assessment of fixed and operational costs (respectively noted CAPEX and OPEX) is conducted. First, a literature review of environmental impact assessment on refrigeration systems is presented. Goal and scope are detailed in the second part, followed by the used methods and material. The results obtained for this study are analyzed. Finally, conclusion and perspectives of this work will complete this article.

## LITERATURE BACKGROUND

After the Kyoto protocols and the F-Gas regulation, studies were conducted to find replacement as effective as previous refrigerants and environmental-friendlier. Environmental impacts of refrigeration systems can be assessed using different methods and different indices. The most commonly used are: global warming potential (GWP) measured in mass of equivalent carbon dioxide ($CO_{2eq}$); Total equivalent Warming impact (TEWI) metric which considers direct and indirect emissions of a refrigeration system [8]–[10]; Life Cycle Climate Performance (LCCP) [11], [12]; LCA [13]–[15]; Carbon Footprint Assessment (CFA). The studies using TEWI metric are mostly developed to compare environmental impacts of traditionally used refrigerants such as ChloroFluoroCarbons (CFCs) or HydroFluoroCarbons (HFCs) gases with more environmental-friendly refrigerants such as natural gases (Ammonia or $CO_2$). LCA and CFA are both standardized methodologies used to assess environmental impacts of refrigeration systems. While the life cycle inventory and system boundaries are more detailed with CFA, only GHG emission and climate change potential are assessed. They are often used to provide a comparison of the energy consumption of different systems architecture that is usually assessed in a unique scenario.

A literature review of refrigeration systems environmental impact assessment shows the lack of published work and data availability. The authors of these studies highlight the importance of the system's energy consumption towards climate change indicators. Indeed, it is the most influencing factor during the use phase of the system lifetime.

## GOAL AND SCOPE

### Goal

This work aimed at analyzing the impacts and observing the variability of these impacts depending on the location to offer recommendations of the system architecture. According to the hypermarket location, the architectures may have different environmental impacts. Thus, it will allow us to have a global vision to identify the most influencing parameters. In future work, that will lead to the development of reduced models and architecture generation of a refrigeration system in different use cases.

### Scope of the study, boundaries and functional unit

In this study, we consider that the cold production systems are installed and used in a hypermarket with an area of 10 000m$^2$. In some scenarios, photovoltaic panels are installed on the rooftop of the hypermarket. The lifetime of refrigeration systems and of the photovoltaic (PV) panels are 15 years and 20 years respectively.

The refrigeration system can deliver cold energy at 2 temperature range: middle temperature (MT, from 0 °C to 10 °C) and low temperature (LT, from -25 °C to 0 °C). The cold power demands are 450kW for medium temperature (MT) and 150kW for low temperature (LT). Two types of architectures were studies: a centralized direct expansion system and a secondary loop system for MT. The main components of a refrigeration system are evaporator, compressor, condenser and expansion valve. Different refrigerants were compared: R134, R22, R717 and R744.

In the use phase, the system is supplied either by the network electricity (the electric mix depends on the country of location) or by the PV panels or the combination of both solutions.

For this study, the end-of-life of the systems is not considered. It is assumed that no parts are recycled.

Three locations are studied, corresponding to three different climatic areas: Paris, France; Stockholm, Sweden; Toledo, Spain.

The following table summarizes all scenarios and main parameters.

Table 1. Review of the studied scenarios

<table>
<tr><td>System architecture</td><td colspan="6">Centralized direct expansion</td><td colspan="6">Secondary loop for MT</td></tr>
<tr><td>Photovoltaic panels</td><td colspan="3">With</td><td colspan="3">Without</td><td colspan="3">With</td><td colspan="3">Without</td></tr>
<tr><td>Location (electricity mix and sun exposure)</td><td colspan="4">France</td><td colspan="4">Spain</td><td colspan="4">Sweden</td></tr>
<tr><td>Refrigerant (primary and secondary fluids)</td><td colspan="12">R134a, R22, R717, R744</td></tr>
</table>

The life cycle inventory (LCI) of the systems is based on a study of Youbi [13] in 2008, on the manufacturers' databases and on the Eco-invent 3 database. The LCI includes the following phases: the raw materials supply (extraction and manufacturing of raw materials including transportation), the life cycle of the components for each system architecture, transportation, installation and use. Disposal stage and maintenance are not considered due to a lack of available data. Manufacturing, installation and transportation stages are in European representative conditions. Energy use comes from two sources: electricity (country's electric mix) and solar energy (PV). The PV performance takes into account the solar exposure and ambient temperature at that location. The simulation considers the whole system, including the pipelines and the display cabinets' evaporators. An example of the architecture of the system for the baseline scenario is showed in the following figure (figure 1.).

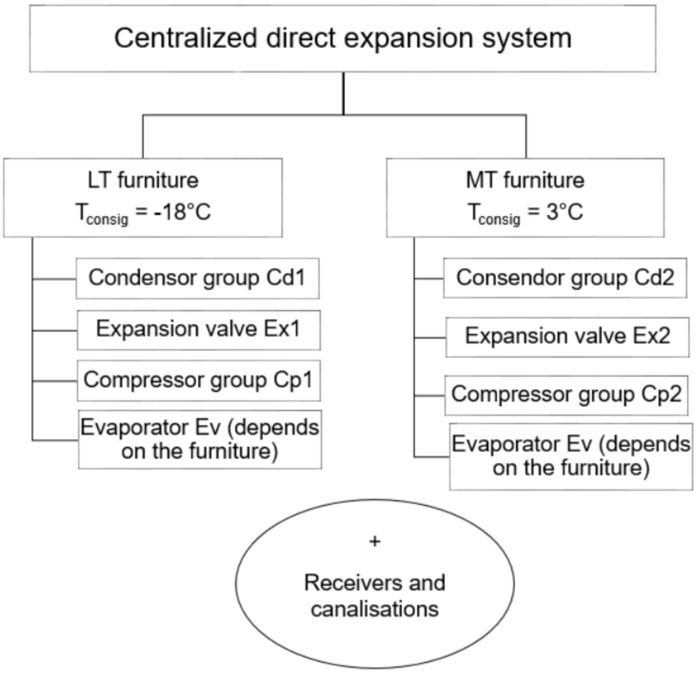


Figure 1. Architecture of the baseline scenario

In our case, the following functional unit is used: a refrigeration system that can provide the cold demand for one hypermarket of 450kW for MT and 150kW for LT at every season (for the hottest day of the year based on the previous years) for fifteen years.

## Simulation tool and data processing

The calculations are carried on SimaPro 8. All the results were then processed by Excel. The Life Cycle Impact Assessment (LCIA) methods used in this study are CML and IMPACT 2002+, respectively a mid-point indicators method and an end-point indicator method.

The cost evaluation of CAPEX (fixed costs) and OPEX (operational costs) are estimated based on components fabrication and installation. The price of 1kWh of electricity is taken for each country.

## RESULTS

Figure 2 presents the global warming indicator obtained for the 4 architectures in France: baseline, refrigeration system using secondary loop, with or without PV panels. The results highlight the significant contribution of electric consumption in the environmental impacts compared to the contribution of refrigerant leakage or of the system components. The secondary loop allows lowering the refrigerant amount in the primary loop which results in a decrease in the climate change indicators compared to the centralized direct systems. Other categories of impacts were calculated and analysed to support the previous statement.

The relation between the architecture choices and cost (CAPEX and OPEX) can be observed in figure 3 for 3 cities: Paris, Toledo and Stockholm. Higher costs are obtained for Indirect systems, which demand more components A significant difference between the countries have been noticed, mostly due to the difference in electricity production and climate conditions. In Spain, using photovoltaic panels helps to reduce efficiently the environmental impacts and the related costs. This scenario is the best alternative compared to the other scenarios. Sweden is the country with the less environmental impacts due to colder climatic conditions (less cold needed) and a favorable electricity mix in terms of $CO_2$ emissions. For both France and Sweden, the use of photovoltaic panels does not bring a significant difference, due to a less sunlight exposition than in Spain.

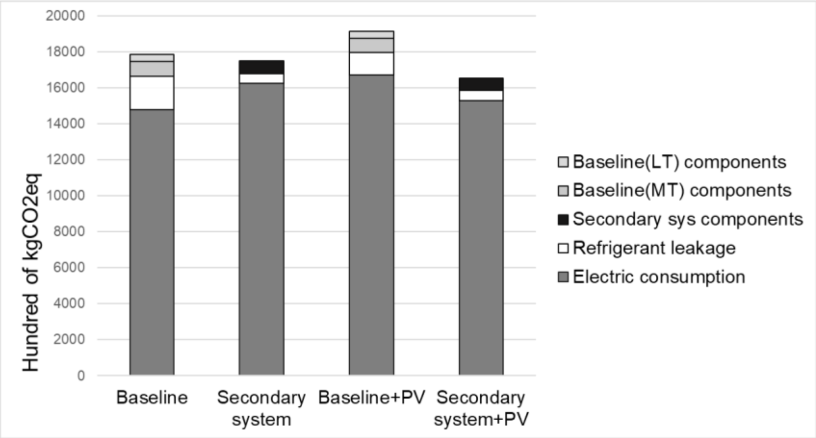


Figure 2. Global warming indicator during the whole lifecycle of the system in France

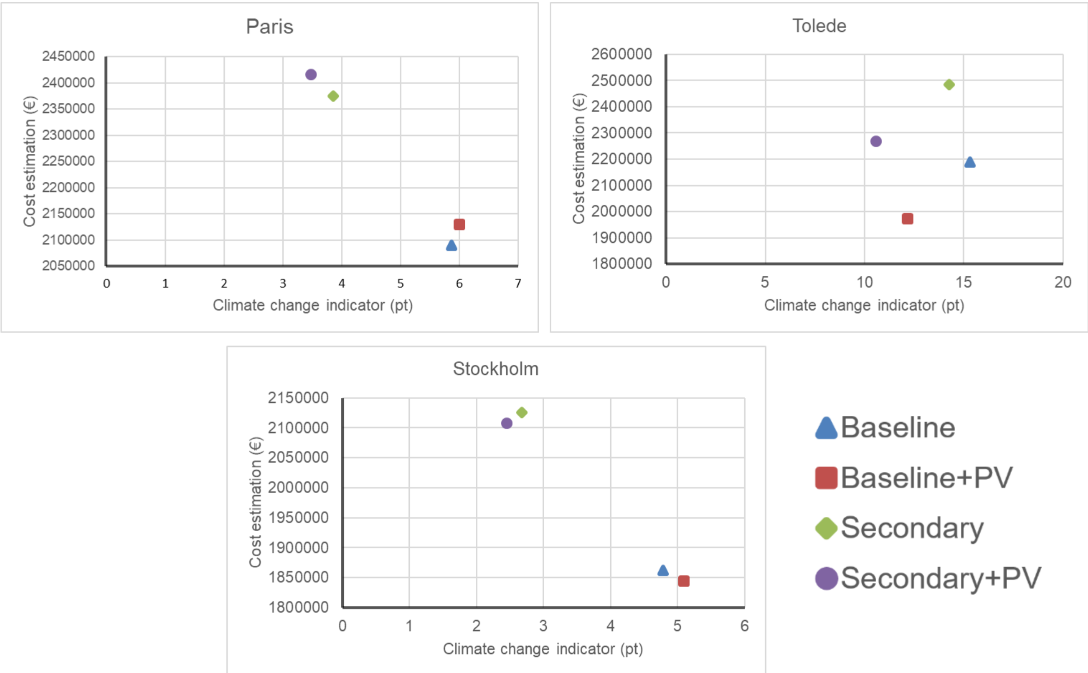


Figure 3. Multi-criteria comparison of systems architectures depending on cost estimation and climate change indicator

## CONCLUSION AND PERSPECTIVES

A first LCA of refrigeration systems under different conditions has been performed. Different parameters are considered and thus generate a set of exploitation scenarios associated with different geographical locations. Once the environmental profiles of these scenarios are identified, costs for each case are estimated. This work highlights the importance of the geographical location to assess the environmental impacts and the economic performances (fixed and operational costs) of the refrigeration system. Indeed, the obtained results show the influence of location on such systems and the necessity to carefully define a relevant context when assessing the sustainability of industrial systems. This study would help decision making and future work perspectives. Global recommendations can not be relevant for every stores as the type of architecture, technology and expectations are different. It is thus interesting to develop a more general model.

This model will be improved by considering more influencing parameters: refining and completing data, including recyclability and waste disposal, maintenance, operational conditions (defrosting, door opening…). Future works could consider other industrial case studies, different technologies and uncertainties related to the system. Afterward, a reduced parameterized model with the most influencing parameters will help the assessment of hypermarket refrigeration systems and decision-making.

## REFERENCES


[1] D. Coulomb, J.-L. Dupont, and A. Pichard, 'The Role of Refrigeration in the Global Economy', Institut International du Froid (IIF), 29th Informatory Note on Refrigeration Technologies, Nov. 2015.

[2] S. A. Tassou, Y. Ge, A. Hadawey, and D. Marriott, 'Energy consumption and conservation in food retailing', *Applied Thermal Engineering*, vol. 31, no. 2–3, pp. 147–156, 2011.

[3] ISO 14044, 'Environmental management -- Life cycle assessment -- Requirements and guidelines', 2006.

[4] 'Kyoto Protocol to the United Nations Framework Convention on Climate Change', U.N. Doc FCCC/CP/1997/7/Add.1, Dec. 1997.

[5] ASHRAE, *ASHRAE Handbook—HVAC Systems and Equipment*. ASHRAE Atlanta, GA, 2008.

[6] ANSI/ASHRAE, 'Standard 34 : Designation and Safety Classification of Refriegrants.' American Society of Heating, Refregerating and Air-Conditionning Engineers, Inc, 2013.

[7] ISO 817:2014, 'Refrigerants - Designation and safety classification'.

[8] R. Maykot, G. C. Weber, and R. A. Maciel, 'Using the TEWI methodology to evaluate alternative refrigeration technologies', 2004.

[9] C. Aprea, A. Greco, and A. Maiorino, 'An experimental evaluation of the greenhouse effect in the substitution of R134a with CO2', *Energy*, vol. 45, no. 1, pp. 753–761, Sep. 2012.

[10] Md. A. Islam, K. Srinivasan, K. Thu, and B. B. Saha, 'Assessment of total equivalent warming impact (TEWI) of supermarket refrigeration systems', *International Journal of Hydrogen Energy*, vol. 42, no. 43, pp. 26973–26983, Oct. 2017.

[11] Y. Hwang, D.-H. Jin, and R. Radermacher, 'Comparison of R-290 and two HFC blends for walk-in refrigeration systems', *International Journal of Refrigeration*, vol. 30, no. 4, pp. 633–641, Jun. 2007.

[12] M. Beshr, V. Aute, V. Sharma, O. Abdelaziz, B. Fricke, and R. Radermacher, 'A comparative study on the environmental impact of supermarket refrigeration systems using low GWP refrigerants', *International Journal of Refrigeration*, vol. 56, pp. 154–164, Aug. 2015.

[13] M. Youbi-Idrissi, 'L'ACV : un outil d'aide à l'évaluation de l'impact environnemental des systèmes frigorifiques', *Revue Générale du Froid et du condionnement d'air*, vol. 11063, pp. 60–67, May 2006.

[14] M. Bovea, R. Cabello, and D. Querol, ‘Comparative life cycle assessment of commonly used refrigerants in commercial refrigeration systems’, *Int J LCA*, vol. 12, pp. 299–307, Jul. 2007.
[15] A. Cascini, M. Gamberi, C. Mora, M. Rosano, and M. Bortolini, ‘Comparative Carbon Footprint Assessment of commercial walk-in refrigeration systems under different use configurations’, *Journal of Cleaner Production*, vol. 112, pp. 3998–4011, Jan. 2016.