Abstract:

Purpose

The design of refrigeration systems must comply with the rules determined by the increasingly stringent international guidelines on the use of refrigerants. Nevertheless, the use of fluorinated gases with low Global Warming Potential (GWP) is a necessary but not sufficient condition for the eco-design of a refrigeration system. Indeed, regardless of the restrictions imposed, the compliance to the best practices of eco-design may be considered as a competitive lever in the contemporary market, which is more and more characterized by the sensitivity to the sustainability issue. In this paper the environmental impact associated with the life cycle of a commercial refrigerator system is investigated. The environmental burden caused by the adoption of alternative refrigerants and different use configurations is evaluated and discussed.

Methodology/Approach

In this study, Life Cycle Assessment (LCA) is the methodology through which the environmental burden introduced by the couple refrigerator-refrigerant is estimated. Life Cycle Impact Assessment (LCIA) step is conducted through the evaluation of the Carbon Footprint associated with each phase of the life cycle of both refrigerant blend and refrigerator. LCIA results are used as Key Performance Indices (KPI) in the final evaluation of the most sustainable solution.

Originality/Value

This article shows an extended application of the LCA as a useful tool in the design of a complex product: eco-design principles are applied in order to identify the best device configuration. Furthermore, one of the main hotspot of this research is represented by the analysed device. Indeed, although the environmental impact of refrigerants is widely investigated, the analysis of the life cycle of a refrigeration system is, as the literature demonstrates, a topic not sufficiently discussed.

Keywords: Design for Environment, Fluorinated Gas, Refrigerator, Life Cycle Assessment, Global Warming Potential.

1. Introduction

Nowadays the continuous improvement of refrigeration devices is one of the most current issues in research context. The growing demand for air-conditioning devices and the equally growing concern about the environmental effects due to their use is pushing the industry, the scientific community and governments to identify efficient and sustainable solutions. The latest European directives related to the manufacture and use of refrigeration systems (i.e. European Regulation 842/2006; European Directive 40/2006), define a clear and undeniable strategy: the use of high GWP refrigerants should be gradually restricted and equipment manufacturers must adapt their products to the use of refrigerants with no environmental impact. The issuing of the European Directive 29/2009 (as known as “20/20/20 climate and energy package”) further accelerated the sustainability program: the European Legislative Proposal 2012/0305 define impending times of decommissioning of hydro fluoro carbon (HFC) gases with GWP greater than 150 (2017-2020). Furthermore, refrigerating systems, as well as all other energy related products, must provide high efficiency and low energy consumption in order to minimise indirect pollutant emissions (European Directive 125/2009). So, the new challenge is the identification of technological solutions that guarantee high performance, low energy consumption and the use of fluids with lower...
GWP index. Aprea et al. (2012) tested the effect of the substitution of R-134a with R-744 (CO₂) in some refrigerating systems on the Total Equivalent Warming Impact (TEWI) value: the study demonstrates that the indirect contribution to global warming provided by R-744 is often greater than that of R-134a. Davies & Caretta (2003) do not focus on refrigerant substitution but concentrate on the identification of design techniques that improve the performance of direct expansion systems regardless of the gas used: they predict substantial savings of energy even in the case of adoption of conventional HFCs (i.e. R-404a, R-410a). Sogut et al. (2012) analyse supermarket cooling applications by estimating their energetic and exergetic performance: R-22, R-502, R-404a, R-507, R-407C, R-152a, R-134a are tested in different systems (i.e. centralized, condensing and stand-alone units) under different assumptions of gas leakage rate. The present paper presents a Life Cycle Assessment study aimed at the evaluation of the environmental impact caused by a refrigerating system throughout its life cycle. According to the authors LCA methodology can be used as instrument for an extensive and complete evaluation of the sustainability of a refrigerating system. Differently from the other studies in which the phases of manufacturing and End-of-Life (EOL) of refrigerator and refrigerant are marginally considered or completely neglected, in this study the whole life cycle of the couple gas-plant is considered and evaluated.

2. Materials and Methods

2.1 Introduction to LCA

The LCA methodology is a tool for the evaluation of the environmental impact associated with a specific product/service throughout its life cycle. Topics and steps of the LCA methodology are regulated by the ISO 14040-14044. In this study SimaPro 7.3.3 software was used as support. However, the omission of such activities cannot be regarded as decisive in the study results. Manual activities of assembly, disassembly and handling were not included in the study due to their negligible environmental impact.

Some so-called “infrastructure processes” (i.e. the life cycle of equipment and tools interacting with the refrigerator and the refrigerants) were not taken into account in order to simplify the analysis process.

2.2 Goal and scope definition

The study is aimed at the evaluation of the environmental performance of a commercial cooling unit (henceforward “MT”), suitable for the cooling at medium temperature range (-5°C+5°C) of small to medium size cells. The evaluation is aimed at highlighting: the different environmental impacts associated with the use of this product; the environmental effects introduced by certain use configuration; the environmental benefit caused by some retrofit such as the replacement of the conventional refrigerator. In this study the assessment of the environmental impact is understood as the evaluation of the Carbon Footprint (CF). So, global warming and climate change are the only effects on the environment assessed. The functional unit expresses and identifies the object of the analysis. The functional unit chosen in this study corresponds to the whole life cycle, from the cradle to the grave, of the couple refrigerator-refrigerant, where the refrigerator is the abovementioned MT and the refrigerant is a fluorinated gas and its amount is related to the refrigerator requirements. This functional unit is the basis from which comparisons between alternative design solutions presented in this study are made, and represents the starting point for potential future comparative analyses.

2.3 System boundaries

The anthropic activities considered in this analysis are represented and ordered in Figure 1. For each one of the sub-systems (refrigerator and gas) three main life cycle phases are distinguished: manufacturing, use-phase and End-of-Life (EOL). The use-phases of device and refrigerant are conjointly considered: the performance of the former is influenced by the characteristics of the latter as well as the leakage rate of the gas is conditioned by the mechanical characteristics of the refrigerator, e.g. the compression ratio and the piping tightness.

![Figure 1: System boundaries](image-url)
2.4 Data category and source

The inventory analysis (LCI) was conducted by the collection of information from different sources. The Original Equipment Manufacturer of the refrigerator (henceforward ROEM) provided information on the composition of the MT, the characteristics of its components, the geographical position of certain suppliers and subcontractors. All processes carried out upstream of the activities performed by the RM, as well as the EOF treatment of MT and refrigerant, were reconstructed through hypotheses and with the support of literature data. Data on energy consumption during use of the system and its efficiency in various configurations were obtained through tests carried out at DIN laboratory (University of Bologna). Due to the lack of specific data on refrigerant leakage rate, some assumptions supported by literature data are proposed. Table 1 shows categories and sources of the data used within the LCI phase. “Specific data” refers to the data strictly related to the specific case study and collected from the direct observation of the manufacturing processes carried out within the ROEM plant. “Generic data” are the data retrieved from literature, or scientific publications, academic papers, relevant LCA studies, and the LCA professional database Ecoinvent v2.2.

2.5 Scenario definition

In agreement with the functional unit, the life cycle of MT is analyzed as a function of a defined utilisation scenario. In fact, the variety of the possible configurations (e.g. type of exchangers and compressor) and conditions (e.g. room setpoint temperature, outside temperature, insulation technique) do not allow to define a unique and representative value of environmental impact. Therefore, a main scenario, as first instance, is defined. The characteristics of the main scenario are listed below:

- The MT is equipped with a micro-channel condenser, a plate fin evaporator, an hermetic reciprocating compressor with a nominal refrigerating capacity of 0.56 kW, and a capillary tube as expansion system;
- The MT contains the fluorinated refrigerant blend R-404A in an amount equal to 350 g;
- It is assumed that the refrigerant gas is dispersed into the atmosphere, every year, for a quantity equal to 10% of the charge in the plant.
- During its life cycle the refrigerator is used for the conditioning of a refrigerating room having external dimensions 1800 x 1800 x 2100 (h) mm;
- The refrigerating room is insulated by a layer of 100 mm of polyurethane foam and a double layer in stainless steel. The overall heat transfer coefficient of the room is estimated to be 8.2 Watts/Kelvin [W/K];
- The MT and the refrigerating room are placed in an industrial/commercial working area: the average temperature throughout the year of about 21 degrees is estimated;
- The temperature set point (or target temperature) of the cell is 0 °C. This is equivalent to the midpoint of the temperature range in which the device can operate, according to the specifications;
- The MT has a service life of 15 years at the end of which the residual gas is recovered and its 70% regenerated and reused, while the plant is disposed as a WEEE (Waste from Electrical and Electronic Equipment).

2.6 Life Cycle Inventory

2.6.1 Manufacturing

The refrigerator MT is made of the following main parts: an hermetic reciprocating compressor, a copper-aluminium plate fin evaporator, an aluminium micro-channel condenser, two fans powered by electric motors, an electronic control unit, copper piping, valves, and a steel/plastic support frame. Thanks to the direct observation of the object a detailed material accounting has been possible. The MT refrigerator, which has a total weight of about 56 kg, is mainly composed of steel and cast iron: 79.7 % by weight. Copper and aluminium are also present for a percentage of 9.7% and 6.3%, respectively. The quantity of thermoplastics (i.e. polyethylene, polypropylene, nylon) and rubbers is limited to 3.7%.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Process</th>
<th>Data category</th>
<th>Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refrigerator</td>
<td>Raw material transformation</td>
<td>Generic</td>
<td>Ecoinvent + Literature</td>
</tr>
<tr>
<td>manufacturing</td>
<td>Manufacturing of components</td>
<td>Specific</td>
<td>Ecoinvent + ROEM</td>
</tr>
<tr>
<td></td>
<td>Assembly</td>
<td>Specific</td>
<td>ROEM</td>
</tr>
<tr>
<td>Gas production</td>
<td>Raw material transformation</td>
<td>Generic</td>
<td>Ecoinvent + Literature</td>
</tr>
<tr>
<td></td>
<td>Manufacturing of components</td>
<td>Generic</td>
<td>Ecoinvent + Literature</td>
</tr>
<tr>
<td></td>
<td>Blend production</td>
<td>Generic</td>
<td>Ecoinvent + Literature</td>
</tr>
<tr>
<td>Refrigerator-Gas Use</td>
<td>Energy consumption</td>
<td>Specific</td>
<td>Lab Tests</td>
</tr>
<tr>
<td>phase</td>
<td>Performance</td>
<td>Specific</td>
<td>Lab Tests</td>
</tr>
<tr>
<td></td>
<td>Gas leakage rate</td>
<td>Generic</td>
<td>Literature</td>
</tr>
<tr>
<td>Refrigerator EOF</td>
<td>Disassembly</td>
<td>Generic</td>
<td>Literature</td>
</tr>
<tr>
<td></td>
<td>Disposal</td>
<td>Generic</td>
<td>Ecoinvent + Literature</td>
</tr>
<tr>
<td>Gas EOF</td>
<td>Recovery</td>
<td>Generic</td>
<td>Literature</td>
</tr>
<tr>
<td></td>
<td>Regeneration</td>
<td>Generic</td>
<td>Ecoinvent + Literature</td>
</tr>
</tbody>
</table>

Table 1: Data category and source
The main transformation activities accounted in the manufacturing of the cooling device are metalworking processes. The support frame is realized principally by cutting, bending, punching and drilling zinc coated steel sheets. The piping is realized by curving, taping and braze welding copper pipes. Plastic components are obtained by injection moulding or thermoforming. Manufacturing inventory data about the hermetic compressor were extrapolated by the study of Biswas and Rosano (2011). The manufacturing processes of some complex elements (e.g. exchangers, electronic components) were simplified by the estimation of the electric energy consumed during their production. Indeed the consumption of electric energy, thermal energy and raw metals is the most relevant input of the analysed system. Specific data on material and component supplier have been collected in order to estimate the contribution of transportation to the environmental impact of the analysed object. The process inventory on the production of the HFC refrigerant is mainly based on literature data. No detailed information on R-404a manufacturing are available in literature. However, Campbell & McCulloch (1998) and McCulloch & Lindley (2003) show the production phases of R-134a and estimate the related CF. Little (2002) demonstrates that the amount of CO2 equivalent emission during the production of some other popular HFCs (e.g. R-143a, R-152a, R-125, R32) is almost equivalent to the quantity emitted for the production of the same mass of R-134a. Therefore, the manufacturing process data of R-134a included in Ecoinvent v2.2 are assumed to be the source for the estimation of the CF of the production of R-404a gas. The manufacturing phase concludes with the transportation of the MT and its refrigerant charge from the ROEM to the customer: the use of a 24-ton truck and an average distance of 500 km between the two nodes are assumed.

2.6.2 Use phase

During the use phase, two main processes are identified: the use of the MT for the conditioning of the refrigerating room; the leakage of the refrigerant from the refrigerator, its dispersion in the atmosphere, and the consequent restoration of the amount lost. The refrigeration process entails the consumption of low voltage electric energy: its amount is influenced by the MT cooling efficiency and the cooling capacity requested by the room. Given the conditions described in the definition of the main scenario, the heat transfer coefficient of the room ($K_{room}$) and the air temperature gap outside-inside the room ($\Delta T$), and the formula (1), the cooling capacity requested to the system is estimated: 169.74 W.

$$Q_f = K_{room} \cdot \Delta T$$  \hspace{1cm} (1)

Under the same conditions, by lab tests carried out on the refrigerator, the system energy efficiency is estimated as follows:

$$\eta = \frac{Refrigerating \ energy \ produced}{Electric \ energy \ consumed}$$  \hspace{1cm} (2)

This value is different from COP (Coefficient of Performance) measure and includes all values of efficiency of the subsystems that compose the refrigerator. In case of use of R-404a a system efficiency of 1.61 is calculated. Therefore the total quantity of electric energy absorbed by the system in 15 years is calculated: 49.87 Giga joule. In order to estimate the environmental impact given by the power consumption of the system, the electric energy mix of the region in which the system is assumed to operate, must be identified. Figure 2 shows the percentage contributions of renewable and non-renewable energy sources for the production of electric energy in Italy. The amount of imported energy (e.g. nuclear energy from France and Slovenia) is taken into account.

2.6.3 End of life

The EOL of a refrigerating system includes a first phase of remediation, through which the residual refrigerant is recovered. After the remediation the refrigerator and the refrigerant are treated separately. The former is disposed as a WEEE: manual disassembly, hulk shredding, material separation, recycling of materials in different percentages, incinerating or landfill. On the other hand the 70% of the recovered gas can be regenerated by filtering and distillation. The remaining portion may be disposed as hazardous waste by incineration.

3. Results

3.1 Life Cycle Impact Assessment

The purpose of LCIA is to quantify the magnitude of the environmental burden generated by the analysed system throughout its lifespan. Since the environmental impact estimation here proposed consists of the evaluation of the CF, the IPCC 2007 GWP 100a method is used as impact assessment index: the environmental damage is identified with the global warming and its effects is measured in kilograms of equivalent carbon dioxide (kgCO$_2$). The first life cycle step analysed is the manufacturing stage. Thanks
to the collected inventory data, for each MT component the environmental impact associated with its manufacturing, from the cradle to the gate, is estimated. Figure 3 reports the CF associated with the manufacturing of the MT components, ordered in functional groups, and the production of the amount of R-404a used within the cooling unit. In most cases a relationship of proportionality between the CF of the components and their weight is evident. This is due to the low constructive complexity of the parts and to the use of a limited panel of materials. An exception is the electronic controller, which requires a particularly energy-intensive manufacturing process, and the refrigerant gas. Indeed, within the manufacturing processes, the production of R-404a involves the greatest environmental damage.

Figure 3: Carbon Footprint of manufacturing

A wider perspective of the CF of the couple refrigerator-refrigerant is given in Figure 4, which shows the quantity of CO$_2$e associated with each stage of the system life cycle. The CF due to the electric consumption of the plant is quantifiable in an order of magnitude higher than that associated with the manufacturing processes. The environmental load associated with the production of the energy consumed by the plant throughout its service is responsible of the 76.6% of the total CF. Gas leakage is as much relevant: the dispersion of R-404a is responsible of the 20.2% of the CO$_2$e emissions (the GWP index of R-404a is 3922). All other life stages i.e., the device delivery from the ROEM to the customer, the disposal of the refrigerator, seem to be irrelevant. Also the environmental impact of the manufacturing of the refrigerator and the refrigerant appears negligible. An interesting result is given by the negative impact of the refrigerant regeneration: this operation avoid the production of an equal quantity of new refrigerant.

3.2 Environmental benefits of gas replacement

LCIA results suggest that the most impacting stage within the life cycles of the system is the use phase. During the use phase the energetic efficiency, the GWP index of the refrigerant and its leakage rate are the keys of the environmental performance of the system refrigerator-refrigerant. Two alternative fluorinated gases are tested within the MT device: R-407f and R-410a. Aim of the test is the evaluation of the global plant performance after the substitution of R-404a with blends with lower GWP index (1825 for R-407F, 2088 for R-410a). Unlike other low GWP gases (e.g. hydro fluoro olefins, hydrocarbons) these HFCs do not involve any relevant refrigerator design modification. Thanks to further laboratory tests the system efficiency in case of use of R-407f and R-410a is evaluated. Since each gas is distinguished by a specific characteristic curve, the refrigerator-refrigerant performances are tested for different values of room setpoint temperatures. Table 2 summarises the results of the laboratory tests and reports the efficiency value for each gas-setpoint temperature configuration.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Setpoint temperature [°C]</th>
<th>0</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-404a</td>
<td>1.60</td>
<td>1.61</td>
<td>1.62</td>
</tr>
<tr>
<td>R-407f</td>
<td>1.67</td>
<td>1.73</td>
<td>1.74</td>
</tr>
<tr>
<td>R-410a</td>
<td>1.90</td>
<td>1.98</td>
<td>2.04</td>
</tr>
</tbody>
</table>

Table 2: System total efficiency

R-407f determines an increase in the system energy efficiency. However, the best result is given by the use of R-410a: an average increment of the 20% of total efficiency is calculated. An higher energy efficiency involves a better environmental performance.

Figure 4: Carbon Footprint of Life Cycle
Table 3 shows the life cycle CF for each analysed scenario.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Setpoint temperature [°C]</th>
<th>-5</th>
<th>0</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-404a</td>
<td>12094.78</td>
<td>10155.23</td>
<td>8239.61</td>
<td></td>
</tr>
<tr>
<td>R-407f</td>
<td>10586.46</td>
<td>8514.66</td>
<td>6734.261</td>
<td></td>
</tr>
<tr>
<td>R-410a</td>
<td>9597.29</td>
<td>7738.57</td>
<td>6069.42</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Life Cycle Carbon Footprint in different gas-setpoint temperature configurations

To higher setpoint temperatures corresponds a decrease in the required cooling capacity and vice versa: a change of 5 degrees involves an increase (decrease) of more than the 20% of the energy consumption and, in turn, of the product environmental load. As expected the best configuration is observed in correspondence of the use of R-410a with a setpoint temperature of 5°C.

5. Conclusion

This paper presents the results of the environmental impact analysis, conducted through Life Cycle Assessment (LCA) methodology, of a commercial refrigeration system. The first objective is the assessment of the CF of the combination refrigerator-refrigerant within a standard scenario of use. Results show that the sustainability of a refrigeration system utilising a fluorinated gas is first of all determined by its energy efficiency, second by the direct impact of gas leakage, and finally, to a lesser extent, by manufacturing and disposal of both refrigerator and refrigerant. This study is not limited to the demonstration that the design of an energy efficient system is, from an environmental point of view, a priority, but also defines the gap that exists between the phases of manufacture and use from the environmental point of view: energy efficiency of the system refrigerator-refrigerant must be pursued even at the cost of reaching a greater impact in their production. With reference to the specific case study the study demonstrates that it is possible to make significant improvements in refrigeration system sustainability without making any significant changes to the system: although R-404a is replaced with other gases, though with a lower GWP, the CF of the analysed system may decrease by 20-26%. Although the European directives declare the undeniable intention to dismiss HFCs, a careful selection of fluorinated gases may, in the medium term, lead to the simplest solution for manufacturers. This paper aims to be a good example in support of this thesis.

6. Acknowledgements

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7. References


Ecoinvent data v.2.2. Swiss Centre for Life Cycle Inventories. http://www.ecoinvent.ch/


