European Supermarket Refrigeration Systems Eco-Efficiency Considerations

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Eco–Efficiency considerations

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ABSTRACT
Fluorinated hydrocarbon refrigerants have especially in Europe been drawn into the focus of the public debate concerning the background of reducing greenhouse active substances. This debate concentrates mainly on the GWP (Global Warming Potentials) properties of the substances.

To step forward from a material based discussion to a useful dialogue about substances in their respective applications a broad investigation of the relevant systems has to be carried out. This examination should consider the whole life cycle of the application and should refer to ecological as well as to economical aspects. A possible approach to attain this goal is the concept of eco-efficiency.

Within this study the eco-efficiency of 6 different concepts of supermarket refrigeration has been examined and compared. The used refrigerants are R134a, R404A, R717 and R744. The data used for the survey are based on a broad knowledge of the advisory board from refrigerant-, component- and controls-manufactures, plant constructors and supermarket operators and supplemented by real facility data.

The results of the investigation illustrate, that the main drivers for ecological and economical performance are the energy consumption of the refrigeration unit and the loss of refrigerants during operation. The study is able to identify the most eco-efficient refrigeration system and also shows optimisation potentials through the investigated facilities.

This paper summarises the results of the project and shows different variations especially with respect to the optimization potentials.

1. INTRODUCTION
One of the goals of national and international politics is currently the reduction of CO₂ emissions. Fluorinated hydrocarbons (HFC’s) and their use within cooling devices has been drawn into the focus of the public debate especially in Europe.

The way to sustainability is another aspect. Pieter van Geel, Dutch State Secretary for Housing, Spatial Planning and the Environment said:
“Sustainable innovation delivers significant economic benefits, by making more efficient use of materials and energy, and by generating fewer emissions and less waste. Since the EU does not have low wages and cheap resources, we have to compete globally by being innovative. Eco-efficient innovation is good not only for the environment, but also for economic growth and employment.”

The debate about Greenhouse gas emissions is based on a stringent material view, taking only the physical properties of the substances class into account. It does neither consider the whole applications the HFC’s are used in, nor the costs that are related to the substance substitution. Such a narrow focus can end up in misleading results as e.g. the application might have a worse performance with a substitute substance.

To step forward from a solely material based discussion to the useful dialogue about substances in their respective applications a broad investigation of the relevant systems has to be carried out in a holistic approach. This holistic examination should consider the whole life cycle of the application from the exploration of the raw materials to production of components, operation of the application until the end of service life and the recycling. Beside the ecologic aspects also economic aspects should be taken into account always bearing in mind that a reduction of greenhouse gases could be achieved in a cheaper way elsewhere.

A possible approach to attain this goal is the eco-efficiency concept. Based on the obtained results, pros and cons of a technology can be balanced, optimization potentials can be uncovered and recommendations for politics and industry can be deduced. To provide data for the mentioned greenhouse gas discussion, a study has been initiated investigating the eco-efficiency of the application “supermarket refrigeration”. In supermarket refrigeration cost performance and environmental performances are very important aspects. Within this study the eco-efficiency of different concepts of supermarket refrigeration has been examined and compared. The used refrigerants are R134a, R404A, R717 and R744. It will be considered the standard types of refrigeration systems and alternative refrigeration concepts with reduced HFC content or not-in-kind alternatives as refrigerant.

2. THE CONCEPT OF ECO-EFFICIENCY

The evaluation of technology is not easy, particularly if parameters must be weighed against each other. Very often ecological and economical aspects have to be considered in the decision-making process. The concept of eco-efficiency comprise cost and environmental input in a life cycle perspective. It will be a very helpful tool. The concept of eco-efficiency considers economical and ecological aspects by using the Life Cycle Cost Analysis and Life Cycle Assessment [1,2,3,4,5].

The fundamental approach of eco-efficiency can be put in a nutshell as follows: »create more value with less impact«. The term was coined in 1992 by the World Business Council for Sustainable Development (WBCSD) as an essential contribution to sustainable development. Since then, the WBCSD has developed it into a strategy and management concept.

»The WBCSD defines eco-efficiency as being achieved by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle, to a level at least in line with the Earth’s estimated carrying capacity.« [6]

Since both natural resources and financial resources are scarce and subject to competition, a more generic definition is reasonable.

The way to create an eco-efficiency portfolio will be done in 4 steps:

Step 1: Conducting a Life Cycle Assessment and a Life Cycle Cost Analysis of the variations
Step 2: Averaging the LCCA and LCA results of the variations
Step 3: Normalization of the LCCA and LCA results
Step 4: Inserting values into the eco-efficiency portfolio
Step 1: Conducting a Life Cycle Assessment and a Life Cycle Cost Analysis of the variations

<table>
<thead>
<tr>
<th>LCA Impact categories</th>
<th>GWP</th>
<th>ODP</th>
<th>EP</th>
<th>AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost categories</td>
<td>Invest costs</td>
<td>Cost of operation</td>
<td>Capital cost</td>
<td></td>
</tr>
</tbody>
</table>

Step 2: Averaging the LCCA and LCA results of the variations e.g.

<table>
<thead>
<tr>
<th>GWP (kg CO₂ equ.)</th>
<th>System 1</th>
<th>System 2</th>
<th>System 3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCCA Euro</td>
<td>System 1</td>
<td>System 2</td>
<td>System 3</td>
<td>Average</td>
</tr>
</tbody>
</table>

Step 3: Normalization of the LCCA and LCA results

<table>
<thead>
<tr>
<th>GWP (kg CO₂ equ.)</th>
<th>System 1</th>
<th>System 2</th>
<th>System 3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCCA Euro</td>
<td>System 1</td>
<td>System 2</td>
<td>System 3</td>
<td>Average</td>
</tr>
</tbody>
</table>

Step 4: Inserting values into the eco-efficiency portfolio (Figure 1)

![Eco-efficiency Portfolio](chart.png)

Figure 1: Eco-efficiency portfolio
In the study, six different concepts of supermarket refrigeration in Germany have been investigated. The systems considered have a cooling capacity of 100 kW (75 kW medium temperature section, 25 kW low temperature section) and represent a typical class of medium German supermarkets. Table 1 shows the investigated concepts.

### Table 1: Investigated refrigeration concepts

<table>
<thead>
<tr>
<th>medium temperature</th>
<th>low temperature</th>
<th>Installation configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>R 404A DX</td>
<td>R 404A DX</td>
<td></td>
</tr>
<tr>
<td>R 134a DX</td>
<td>R 404A DX</td>
<td></td>
</tr>
<tr>
<td>R 404A (indirect)  brine</td>
<td>R 404A DX</td>
<td></td>
</tr>
<tr>
<td>R 404A DX</td>
<td>R 744 DX</td>
<td>cascade</td>
</tr>
<tr>
<td>R 134a DX</td>
<td>R 744 DX</td>
<td>cascade</td>
</tr>
<tr>
<td>R 717 (indirect)  brine</td>
<td>R 744 DX</td>
<td></td>
</tr>
</tbody>
</table>

### 3.1 Life Cycle Assessment

Life cycle assessment evaluates the impact of material and energy flows in a cradle to grave approach, this means from exploration of raw materials to end of life management. In case of supermarket refrigeration it comprises the production of refrigerants, of the refrigeration unit, the operation of the supermarket including energy supply until the end of life and the disassembly of the unit. As the displays in the show room are assumed to be similar for each refrigeration system they have not been included into the survey.

To assess the life cycle of the investigated systems the variable parameters like material use to produce the systems, energy consumption of the systems, refrigerant charge and refrigerant loss and the life time of the installation have been estimated within the advisory board. To verify the assumptions data from real supermarkets have additionally been processed if available. Table 2 shows the considered values.

### Table 2: Assumptions for calculation

<table>
<thead>
<tr>
<th>Refrigerant charge</th>
<th>kg</th>
<th>R 404A</th>
<th>R 744/ R 404A</th>
<th>R 134a &amp; brine/ R 404A</th>
<th>R 404A/ R 744</th>
<th>R 717/ R 744/ &amp; brine/ R 744</th>
</tr>
</thead>
<tbody>
<tr>
<td>R 404A</td>
<td></td>
<td>330</td>
<td>110</td>
<td>200</td>
<td>270</td>
<td>-</td>
</tr>
<tr>
<td>R 134a</td>
<td></td>
<td>-</td>
<td>200</td>
<td>-</td>
<td>-</td>
<td>245</td>
</tr>
<tr>
<td>R 744 (CO₂)</td>
<td>kg</td>
<td>-</td>
<td>-</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>R 717 (NH₃)</td>
<td>kg</td>
<td>-</td>
<td>-</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Secondary HT fluid charge</td>
<td>kg</td>
<td>-</td>
<td>800</td>
<td>-</td>
<td>1.600</td>
<td></td>
</tr>
<tr>
<td>Average energy consumption</td>
<td>MW/a</td>
<td>224</td>
<td>213</td>
<td>248</td>
<td>228</td>
<td>212</td>
</tr>
<tr>
<td>Average refrigerant loss, filling</td>
<td>%</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Average refrigerant loss, operation</td>
<td>% p.a.</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Average refrigerant loss, disassembly</td>
<td>%</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

### 3.2 Life Cycle Costing

The life cycle costs of the investigated systems have been calculated by taking the investment and energy costs as well as costs for refrigerants and maintenance into account. Costs of investment have been calculated. Energy prices vary from operator to operator thus no clear price can be given. The cost calculations in this study were carried out with a price of 0.1 € per kWh in the first year and an increase of 0.01€ per kWh and year. The costs of maintenance in a first attempt were estimated to be 2 % of the investment costs per year. For financing the interest rate has been assumed to be 4%. The estimated costs of investment and the calculated life cycle costs are listed in Table 3.

### Table 3: Assumed investment costs of the investigated refrigeration systems

<table>
<thead>
<tr>
<th>System</th>
<th>Investment %</th>
<th>Calculated life cycle costs %</th>
</tr>
</thead>
<tbody>
<tr>
<td>R404A/R404A</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>R134a/R404A</td>
<td>108</td>
<td>97,8</td>
</tr>
<tr>
<td>R404A &amp; brine/ R404A</td>
<td>120</td>
<td>115,9</td>
</tr>
<tr>
<td>R404A/ R 744</td>
<td>112</td>
<td>105,4</td>
</tr>
<tr>
<td>R134a/ R 744</td>
<td>120</td>
<td>101,1</td>
</tr>
<tr>
<td>R 717 &amp; brine/ R 744</td>
<td>140</td>
<td>118,3</td>
</tr>
</tbody>
</table>
4. RESULTS AND DISCUSSION

The results of the life cycle assessment and the life cycle costs have been processed to obtain the eco-efficiency portfolio. The average of the life cycle costs of the six compared systems has been set to 1 and the costs of each investigated system have been set in relation to the normalized average value. In analogy to the costs, also the results of LCA have been handled. The average of each environmental impact of the six refrigeration units has been set to 1, the single values then been set in relation to the average impact. The normalized results from this calculation then have been transferred into a coordinate-system. Figure 2 shows the eco-efficiency portfolio of the six investigated refrigeration systems.

![Figure 2: Eco-efficiency portfolio global warming potential of the investigated refrigeration systems (y and x-axis scales in reversed order, x-axis environmental performance, y-axis cost performance)](image)

It can be shown, that, based on the assumptions, the most eco-efficient system is a combination of a R134a system in the medium temperature section and a R744 cascade system in the low temperature section. The R134a/R404A concept also has a good eco-efficiency. Furthermore it can be seen, that the standard option of refrigeration systems (R404A/R404A) is moderately cost effective but has the highest GWP-impact. The investigated ammonia/carbondioxide system could be shown to be the concept with the lowest environmental impacts. But the system has the poorest cost effectiveness. The calculated life cycle costs for the ammonia/carbon dioxide are far higher than the cheapest refrigeration concept R134a/R404A.

The obtained results clearly indicate that decisions based on only a substance view can worsen the situation. An investment into the not usual concept R717 brine / R744 cascade does not show much less environmental impact than the R134a / R744 cascade concept. If the higher invest will be spent for e.g. thermal insulation of buildings, the CO2 - emission reduction would be much higher. The results also show that the cheapest investment is not always the best. Purchasing agents who always focus on the cheapest option may spend more money than a colleague who considers the whole life cycle.

5. SENSITIVITY ANALYSIS

As mentioned, the study also included sensitivity analyses, in which the main system parameters, energy consumption and refrigerant losses, were varied. A first variation of the parameters assumed that the 5% or 3% annual losses of HFC refrigerant charge can be reduced to 2% per annum. Fig. 3 shows the eco-efficiency of the systems in the study.

Figure 3 clearly shows that when refrigerant losses are reduced the environmental burdens of the systems converge. As a result, the systems R404A/R404A and R404A/R744, which previously were less eco-efficient than the R717/R744 cascade, are now more eco-efficient than the version with “natural” refrigerants. The version with R134a/R744 in cascade continues to have the highest eco-efficiency.
In further variations of the parameters, individual system versions were each subjected to an optimization scenario, while the rest of the systems studied were calculated with the standard parameters specified by the consultative group. For the R404A/R404A reference technology, it was assumed that a 20% reduction in energy consumption can be achieved at 15% higher capital cost with optimized technology. In addition, an annual loss of refrigerant of 2% of the refrigerant charge was assumed (Fig. 4).

The optimization of the reference technology leads to a substantial increase in eco-efficiency, compared to the alternatives studied. Assuming reduced energy consumption and reduced losses of refrigerant, the R404A/R404A system achieves the highest eco-efficiency of the system versions studied. The technology not only makes the smallest contribution to the greenhouse effect over the entire life cycle, its life-cycle costs are also the lowest by far, despite the additional investments. This favorable cost situation is due to the savings on energy costs. Besides the reference technology, the R134a/R744 technology in cascade also continues to show high eco-efficiency. Under the assumptions made, however, the eco-efficiency of the ammonia/CO$_2$ technology drops. It is now comparable with the results for the R404A/R744 technology.

As with the reference technology, parameters were also varied for the R134a/R404A version. The changes in the eco-efficiency of this version are considerably larger compared to the parameter variation for the reference technology. In this case, too, the assumption was a reduction in energy consumption of 20% with 15% higher capital costs. The calculations (Fig. 5) also assumed an annual loss of 2% of the refrigerant charge.
The optimized R134a/R404A technology demonstrates greater eco-efficiency than the alternatives included in the study. Under the assumed parameters, this variant is advantageous, from both an environmental and economic point of view.

Figure 5: Eco-efficiency of the units studied with respect to GWP – R134a/R404A optimized

6. POTENTIALS FOR OPTIMIZATION OF ENERGY CONSUMPTION

In testing the sensitivity of the results with respect to energy consumption, we assumed a reduction in energy consumption due to technical and organizational optimization, without considering specific measures. For the sake of completeness, we have compiled several technical and organizational shortcomings, and suggestions for preventing them:

• Too low vaporization temperatures (freezer or cold-storage temperatures)/too high condensation temperatures:
  Suggestion for prevention: Adherence to the storage temperatures for refrigerated goods recommended by the Bundesinstitut für Risikobewertung (BfR) ['Federal Institute of Risk Evaluation']. Installation of intelligent feedback control systems. Installation of electronic expansion valves. Thus adjustment of the condensation temperatures to lower ambient temperatures can be achieved.

• Too high temperatures at storage (caused by unrefrigerated interim storage of the goods, e.g. in front of the supermarket)
  Suggestion for prevention: Prevent interruptions in the cold chain. The goods should be brought directly to the cold-storage facility without any intermediate storage. The temperature at delivery must correspond to the freezer temperature.

• Increased lighting periods / excessive lighting loads
  Suggestion for prevention: Use of energy-efficient lamps. Reduction in number of lamps by use of reflectors. Use of motion detectors. Significant savings in energy can be achieved by screens and canopies that reflect infrared radiation. Grouping of freezers, thus creating cooler zones.

• Too long or frequent periods when doors are open during deliveries/ insufficient insulation and leaks at doors
  Suggestion for prevention: Remedy by employing air locks, fast-action doors, and inflatable seals. The areas between the truck to the cold store should be sealed off.

• Overfilling of freezers / evaporator air grid blocked by goods to be cooled
  Suggestion for prevention: If the maximum stacking heights for freezer chests and islands are not observed, the cold-air curtain will be interrupted. The maximum stacking heights should be adhered to under all circumstances. Furthermore, when filling the freezer, one must be careful not to block the air ducts with the refrigerated goods.

• No daytime and night-time covers on freezers
  Suggestion for prevention: Transparent sliding glass covers and insulated night-time covers minimize the penetration of ambient air, and reduce the effect of infrared irradiation.

• Too small condensers
  Suggestion for prevention: By installing larger condensers, the temperature difference which drives the refrigeration can be optimized. Additional advantages can be achieved by using soldered “micro-channel” heat exchangers, such as improved heat transfer accompanied by a reduction in the quantity of refrigerant.
7. DISCUSSION

Our study of standard variants of supermarket refrigeration systems and our sensitivity analyses show that the refrigeration energy consumption is a major factor in its environmental impact (contribution to global-warming potential). Energy consumption has also been identified as an important factor pushing up life-cycle costs. In view of this, the highest priority must be given to increasing the energy efficiency of existing systems and future installations by optimizing the technology and organization. In this way, environmental impact can be minimized effectively, and large increases in operating costs due to future rises in energy prices can be prevented. In addition to measures to reduce energy consumption, further steps must be taken to minimize losses of refrigerant. This also enables a reduction in environmental impact, and thus an increase in the equipment's eco-efficiency. In addition to the direct emissions of greenhouse gases, energy consumption is also indirectly responsible for the acidification of rain water associated with the emissions from power plants, oxygen depletion in lakes, and ozone pollution. Technologies with a high energy consumption are especially disadvantageous here.

Furthermore, the results of the study show that decision-making based on purely environmental considerations can lead to misjudgements. This applies both to analyses related exclusively to the refrigerant and to those which already take the use of the refrigerant into account, such as the eco-audit. For example, if an exclusively material-based approach were taken, the employment of the R134a/R744 version in cascade would be restricted, due to the use of fluorinated hydrocarbons with a high specific global-warming potential, although this type possesses the best properties, both from the economic and the environmental point of view. A decision based on the results of the eco-audit would favor, besides the version R134a/R744 in cascade, the system R717 brine/R744 cascade as well—although the lower environmental burdens are obtained at a cost which, invested in other technologies, would result in considerably greater savings. In view of this, the results of eco-efficiency analyses should be taken considerably more into account in future decision-making.

Although the results of eco-audits should not be used as the sole basis for decision-making, they do show clear shortcomings of the processes examined. The eco-audit results for the supermarket refrigerating system studied, under the standard parameters, show that the reference technology R404A cooling/ R404A deep freeze has the highest emissions of greenhouse gases. A change of refrigerant from R404A to R134a for cooling helps to reduce the proportion of these emissions considerably. In addition, the refrigerant emissions and the energy consumption of the system could be lowered, due to the characteristics of the R134a compound system. For the existing supermarket refrigerating equipment, most of which corresponds to the R404A/R404A version, the results of the study show that retrofitting the plant, for example with intelligent control systems, would help to increase its eco-efficiency. If the losses of refrigerant can be reduced as well, the R404A/R404A version of refrigerating machinery can become the most eco-efficient variant.

If eco-efficiency can be improved and refrigerant losses minimized in the future, then the R134a/R404A technology has a high potential. The results show that higher energy efficiency alone would make this technology the most eco-efficient version of the equipment studied. A reduction in refrigerant losses would increase this head-start still more.

8. REFERENCES